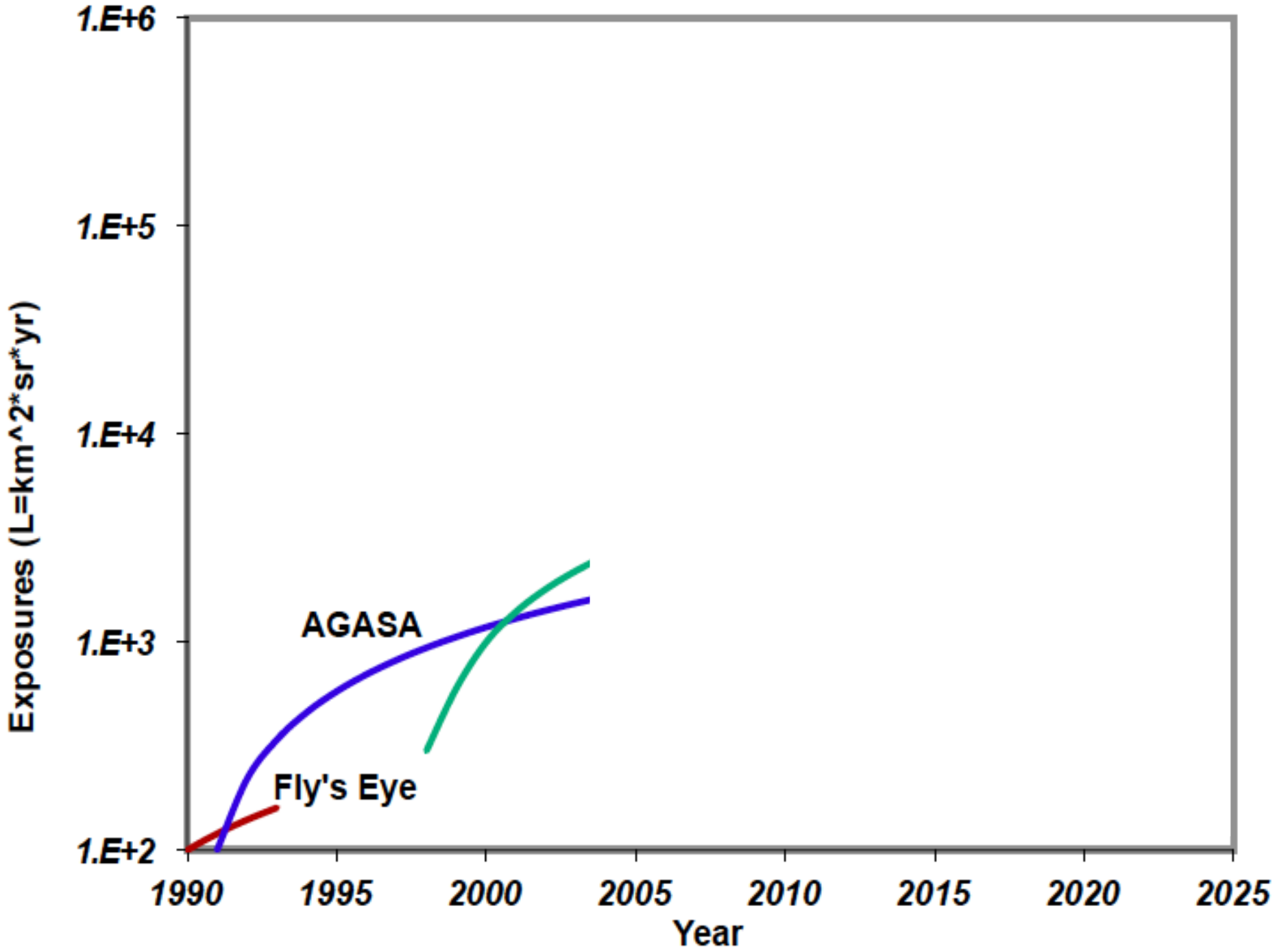
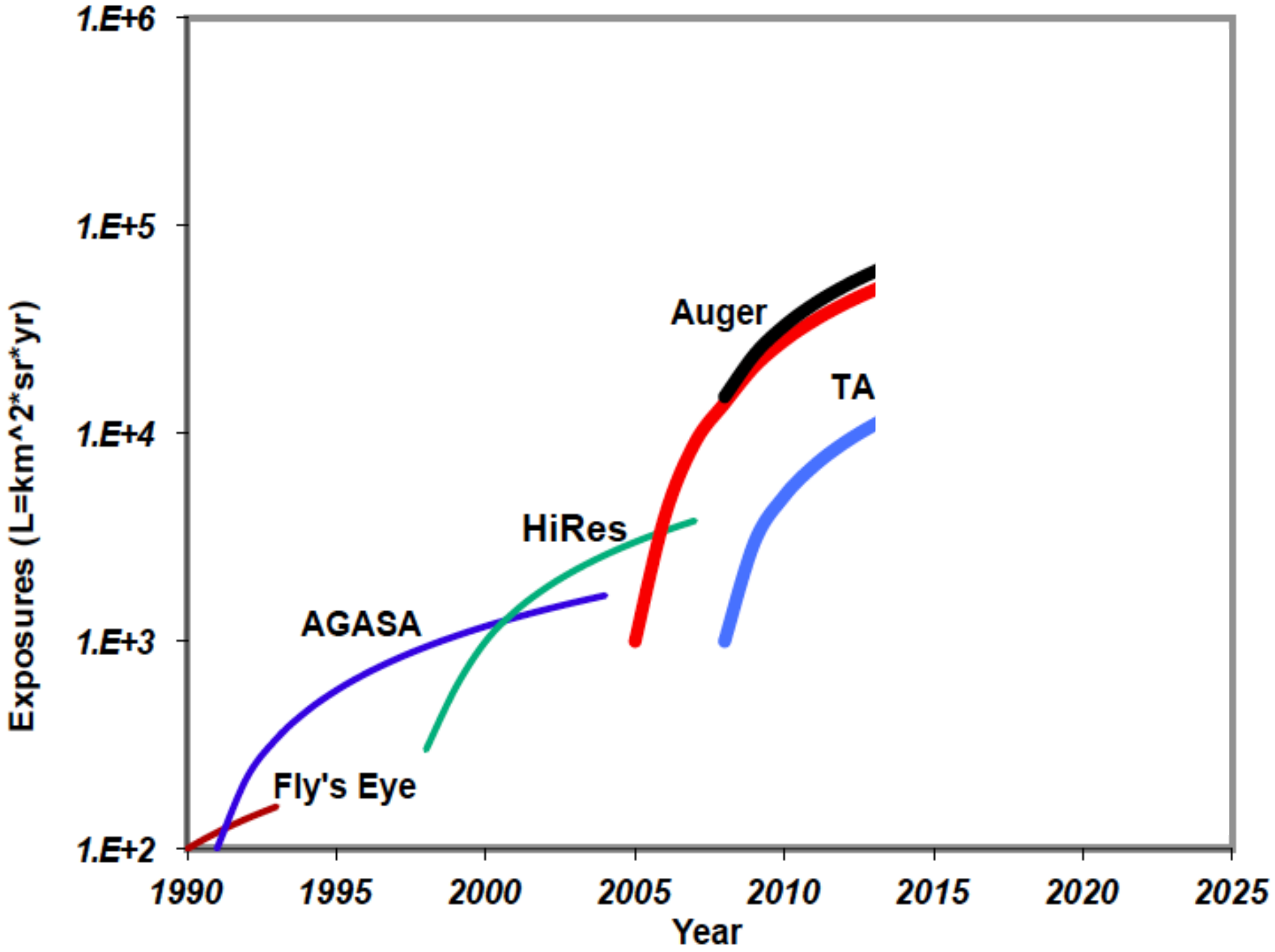
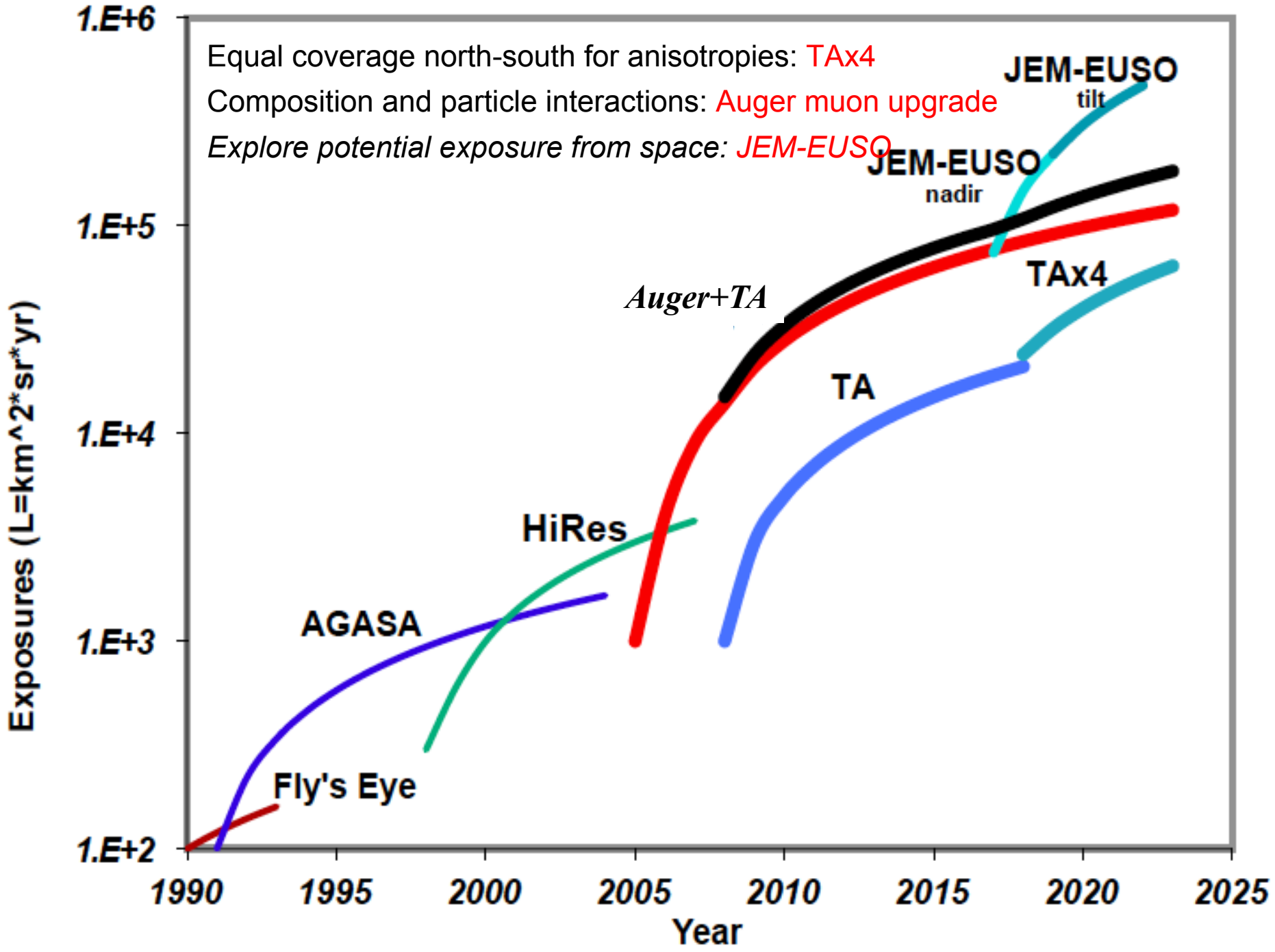

1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
AGASA
Fly's Eye
1990
1995
2000
2005
2010
2015
2020
2025
Year


1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
Auger
TA
HiRes
AGASA
Fly's Eye
1990
1995
2000
2005
2010
2015
2020
2025
Year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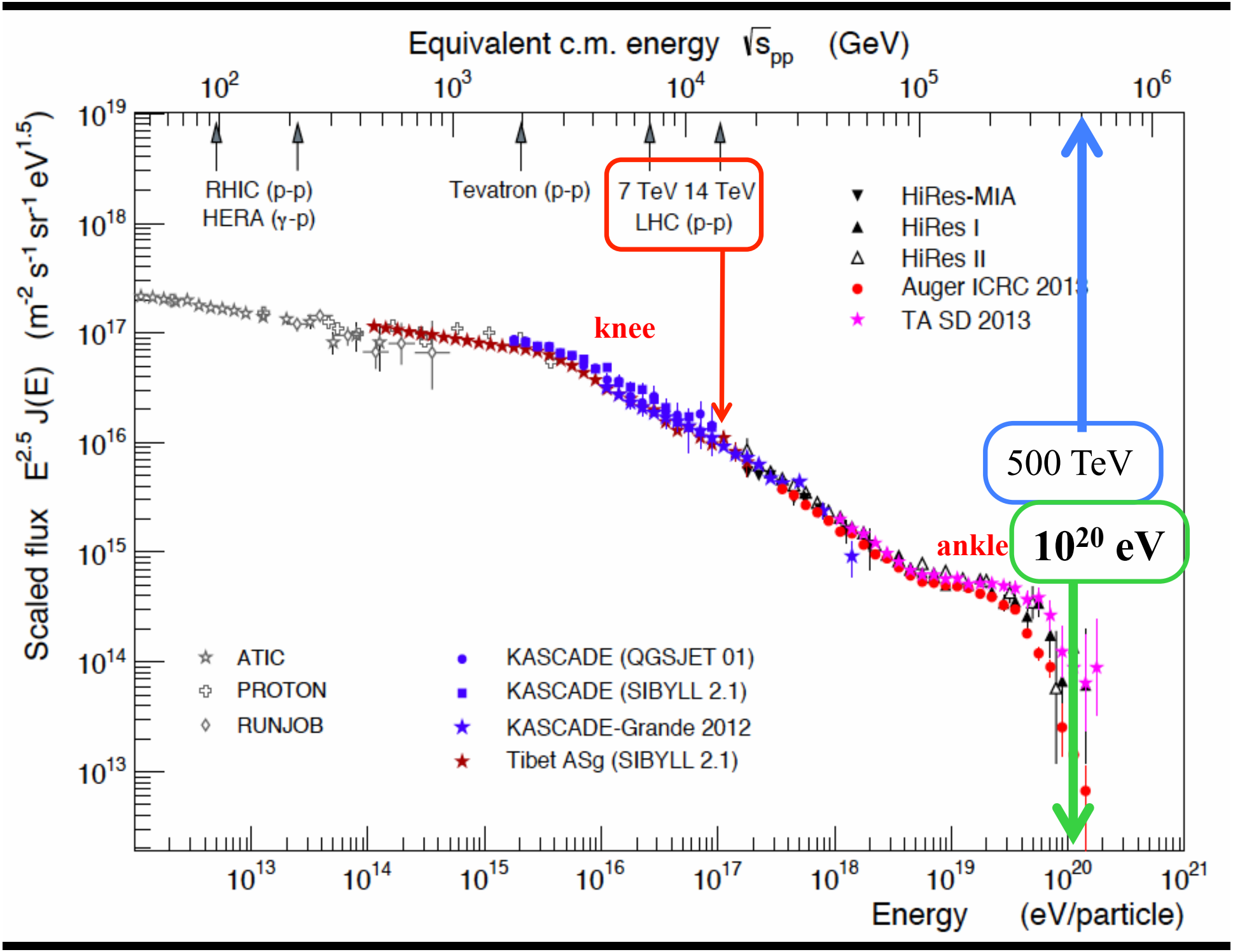
Composition and particle interactions: Auger muon upgrade
Explore potential exposure from space: JEM-EUSO
JEM-EUSO
tilt
JEM-EUSO
nadir
TAx4
Auger+TA
TA
HiRes
AGASA
Fly's Eye
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year


Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
knee
ankle
500 TeV
10^20 eV
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 201
TA SD 2013
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
Energy (eV/particle)
10^19
10^18
10^17
10^16
10^15
10^14
10^13
10^21

Current Observatories of Ultrahigh Energy Cosmic Rays

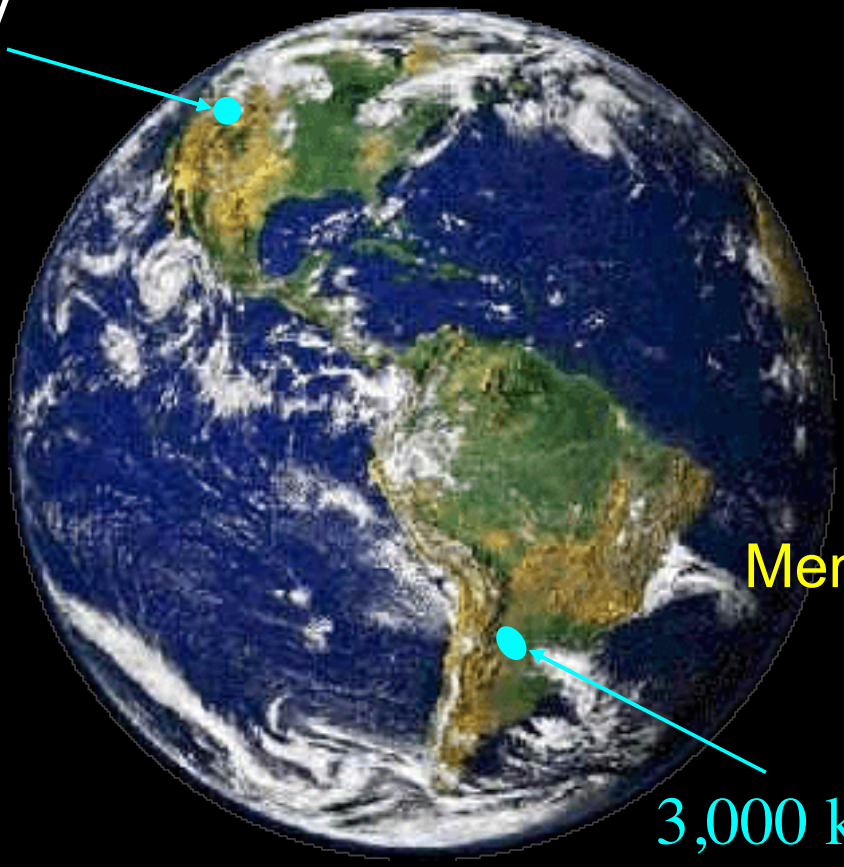
Telescope Array

Utah, USA

(5 country collaboration)

700 km^2 array

3 fluorescence telescopes



Pierre Auger Observatory

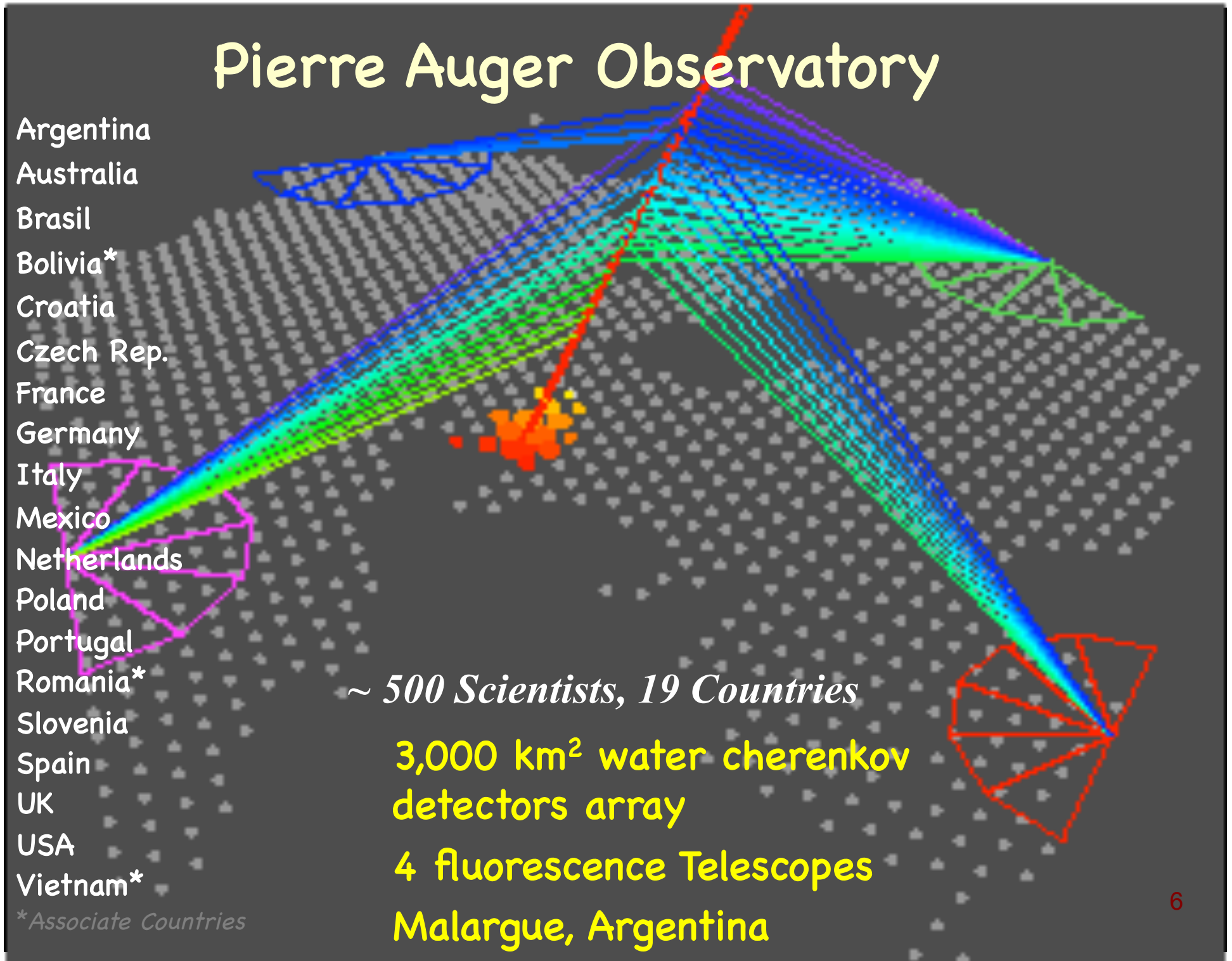
Mendoza, Argentina

(19 country collaboration)

3,000 km^2 array

4 fluorescence telescopes

Pierre Auger Observatory



Argentina
Australia
Brasil
Bolivia*
Croatia
Czech Rep.
France
Germany
Italy
Mexico
Netherlands
Poland
Portugal
Romania*
Slovenia
Spain
UK
USA
Vietnam*

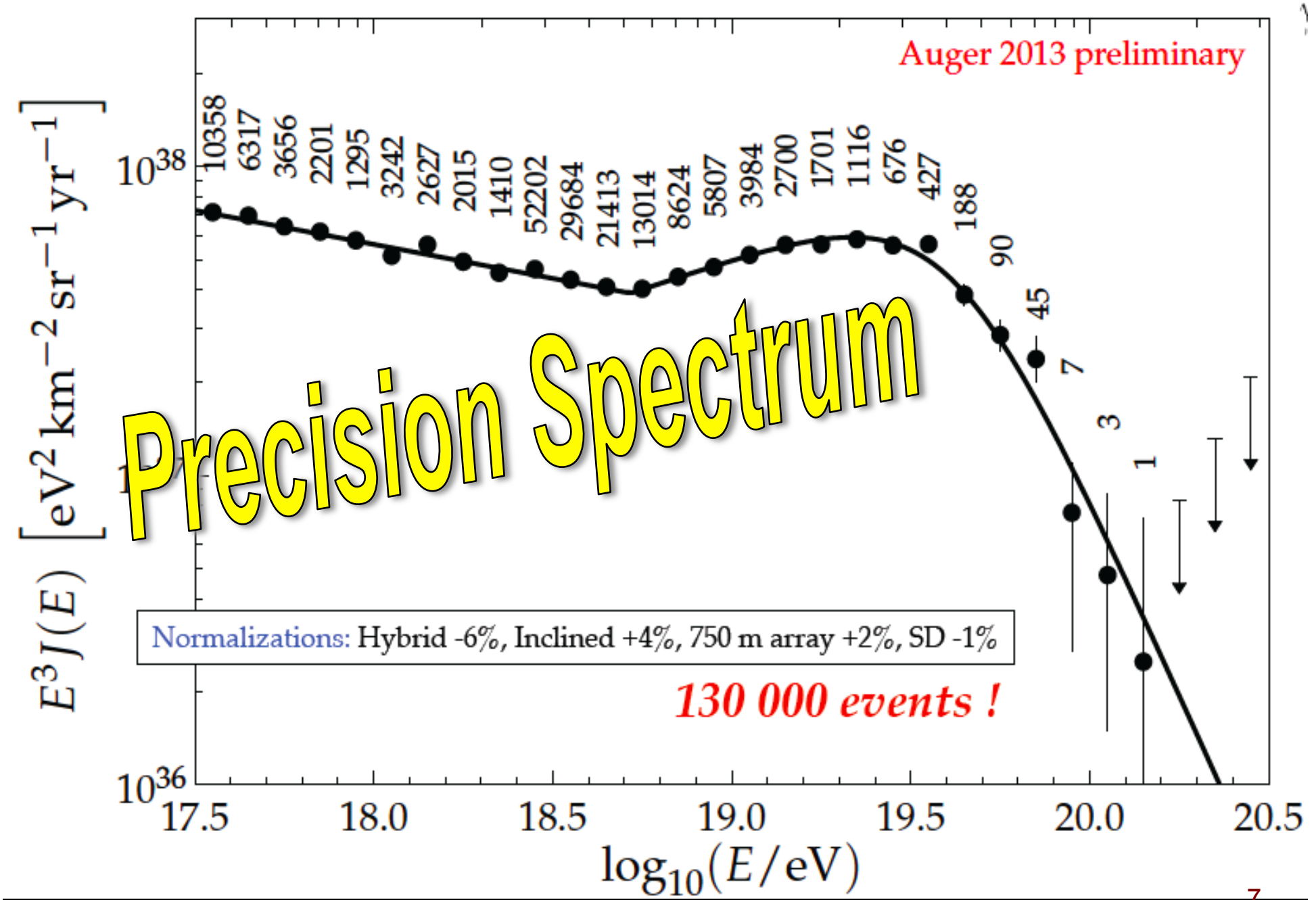
*Associate Countries

~ 500 Scientists, 19 Countries

3,000 km² water cherenkov detectors array

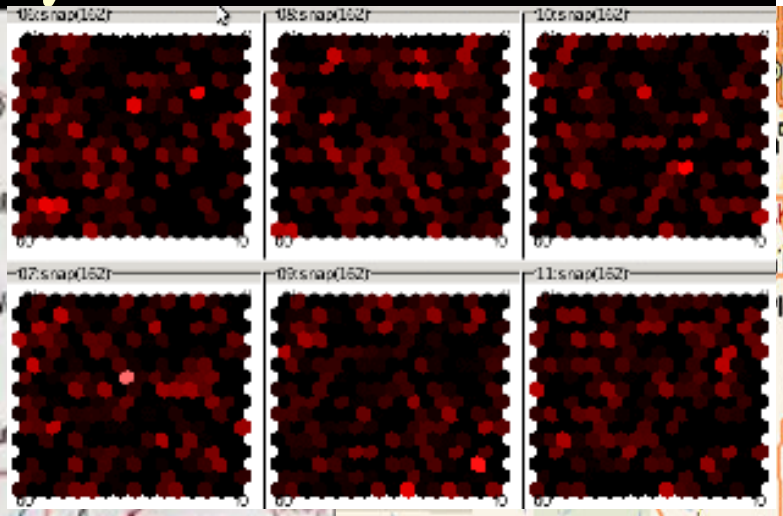
4 fluorescence Telescopes

Malargue, Argentina


Auger 2013 preliminary
Precision Spectrum
10358
6317
3656
2201
1295
3242
2627
2015
1410
52202
29684
21413
13014
8624
5807
3984
2700
1701
1116
676
427
188
90
45
7
3
1
10^{38}
10^{36}
$E^3 J(E)$ $\left[\mathrm{eV}^2\,\mathrm{km}^{-2}\,\mathrm{sr}^{-1}\,\mathrm{yr}^{-1}\right]$
Normalizations: Hybrid -6%, Inclined +4%, 750 m array +2%, SD -1%
130 000 events !
17.5
18.0
18.5
19.0
19.5
20.0
20.5
$\log_{10}(E/\mathrm{eV})$

Telescope Array

Belgium
Japan
Korea
Russia
USA



Area: 700 km^2

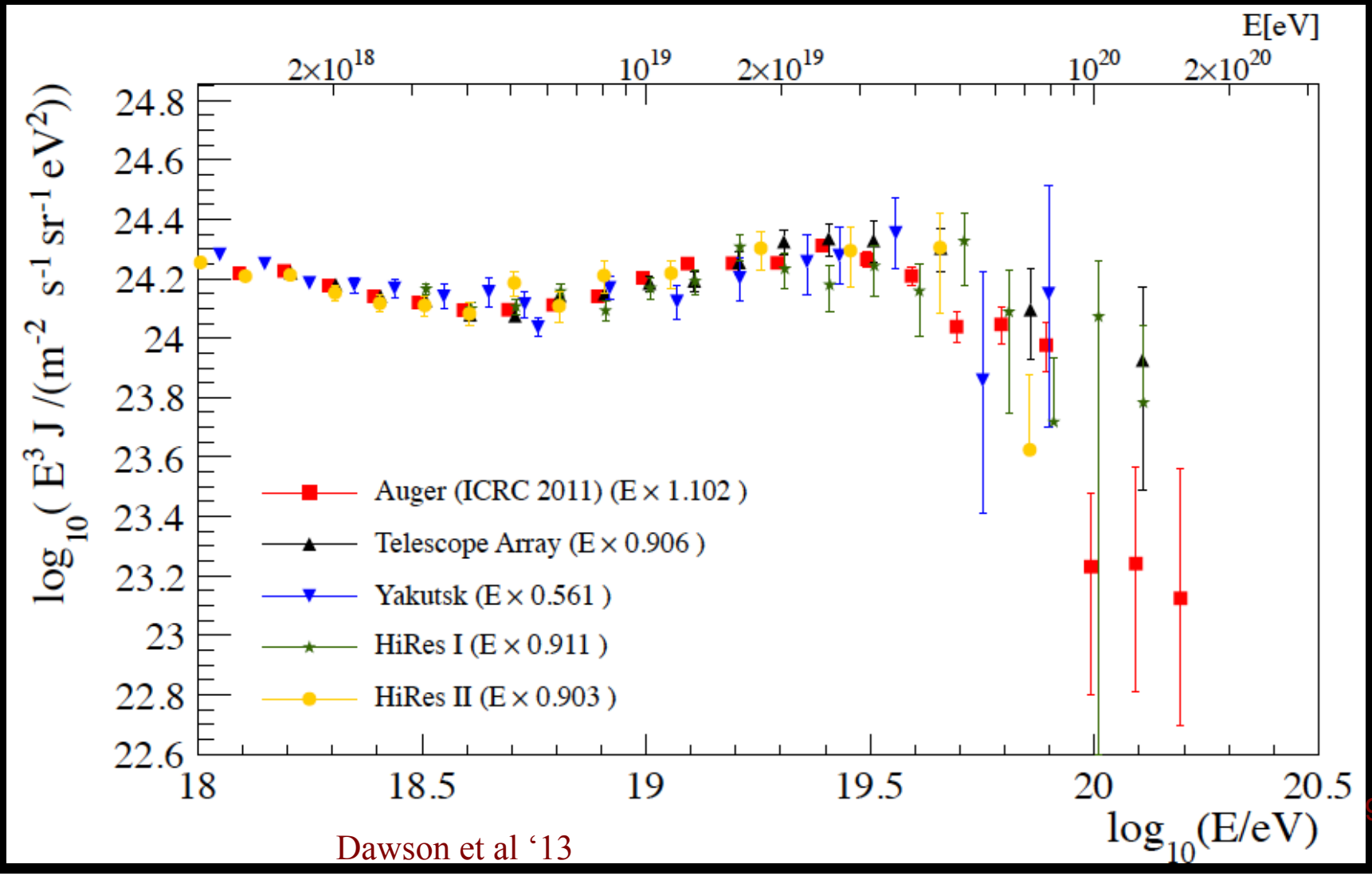
3 FD stations overlooking an array of

507 scintillator surface detectors (SD)

2012 CERN Working Group

Unified Spectrum

Energies re-scaled ~10%



Dawson et al '13

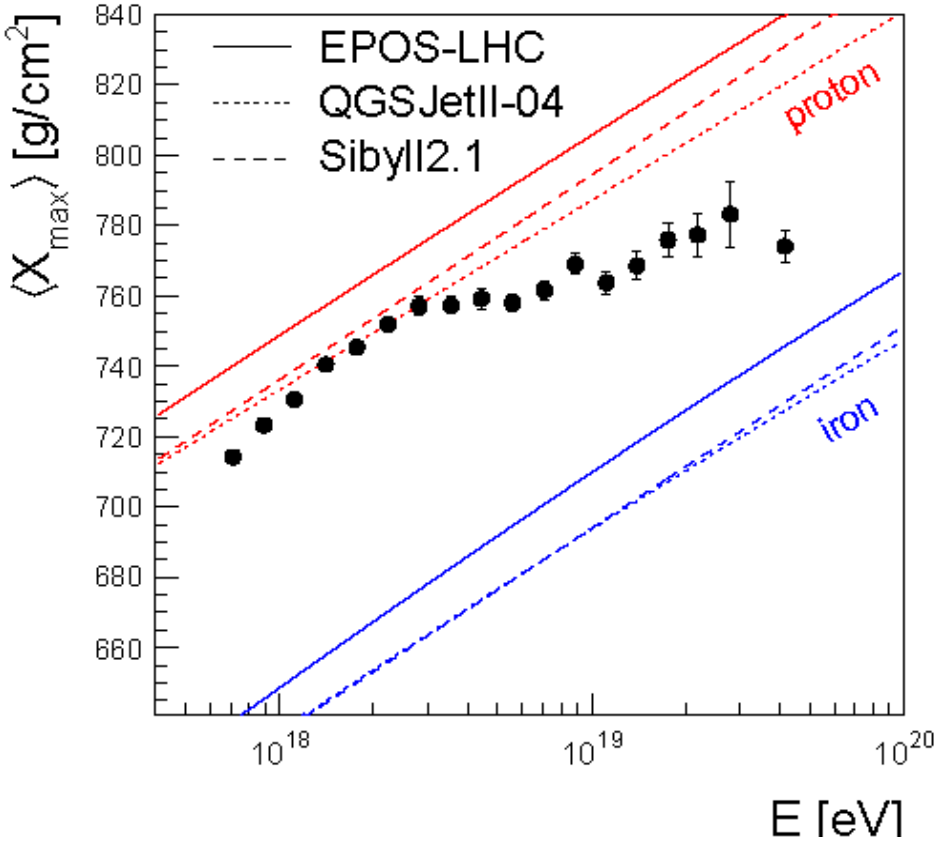
UHECRs Current Status

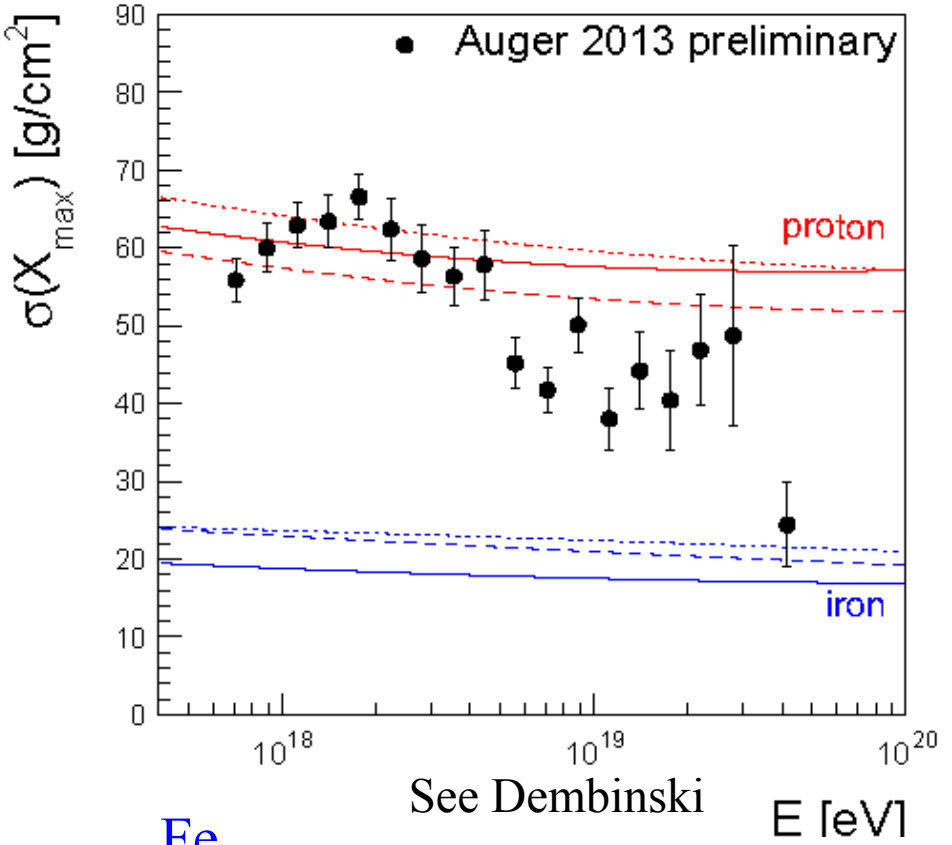
Leading Observatories: Auger & Telescope Array

Agree on the shape of the spectrum

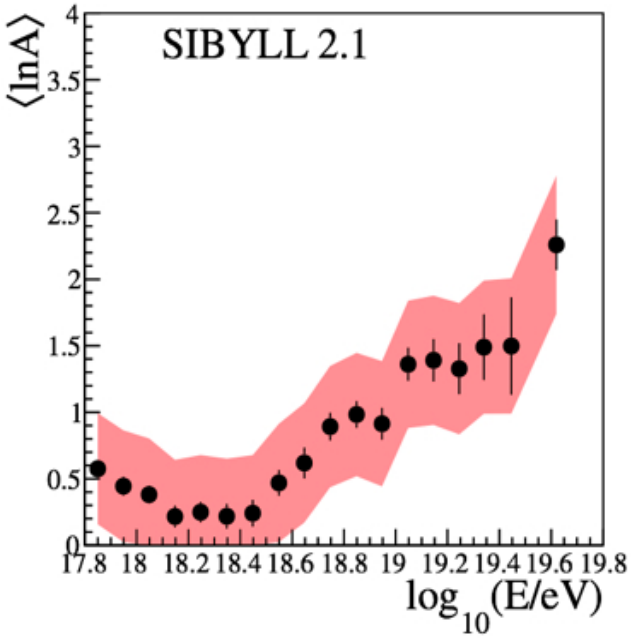
Energy scale: ~10% difference

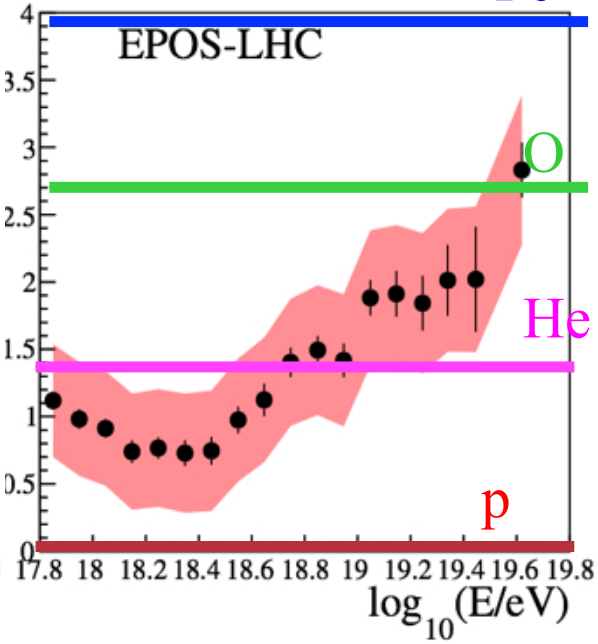
Composition?

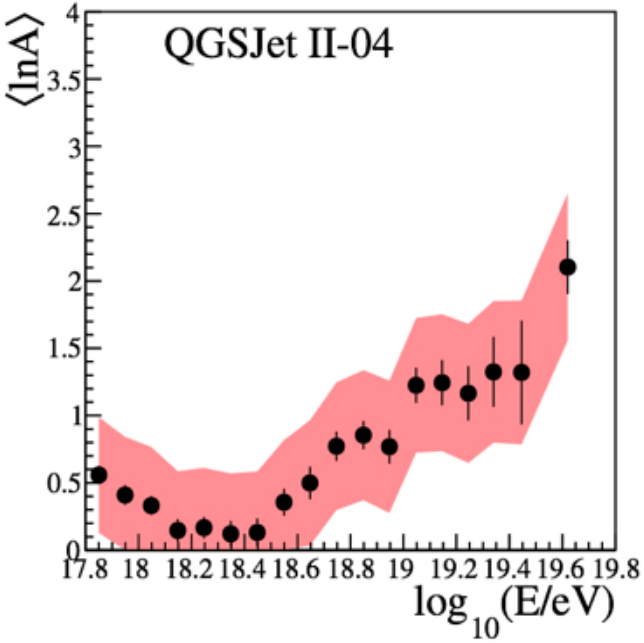


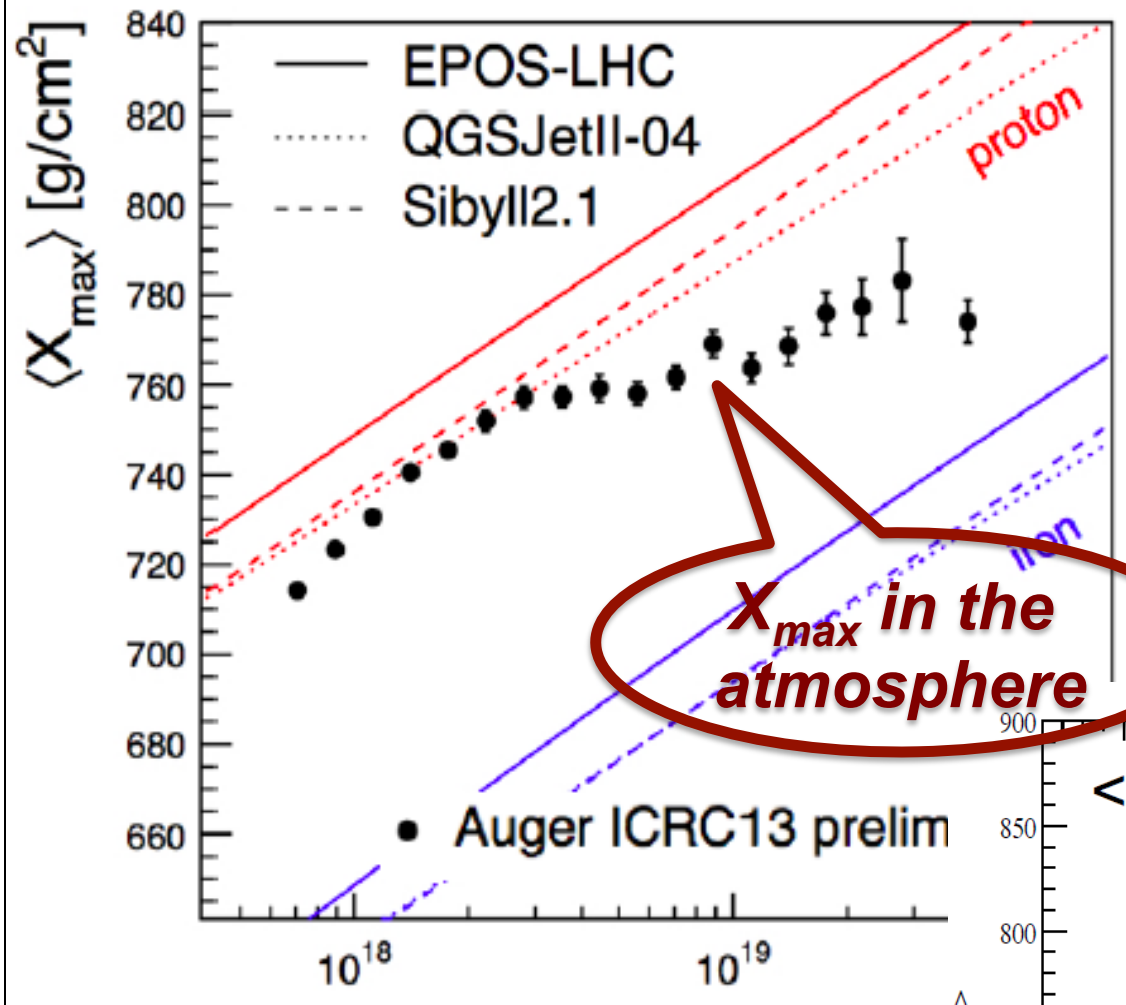


See Dembinski





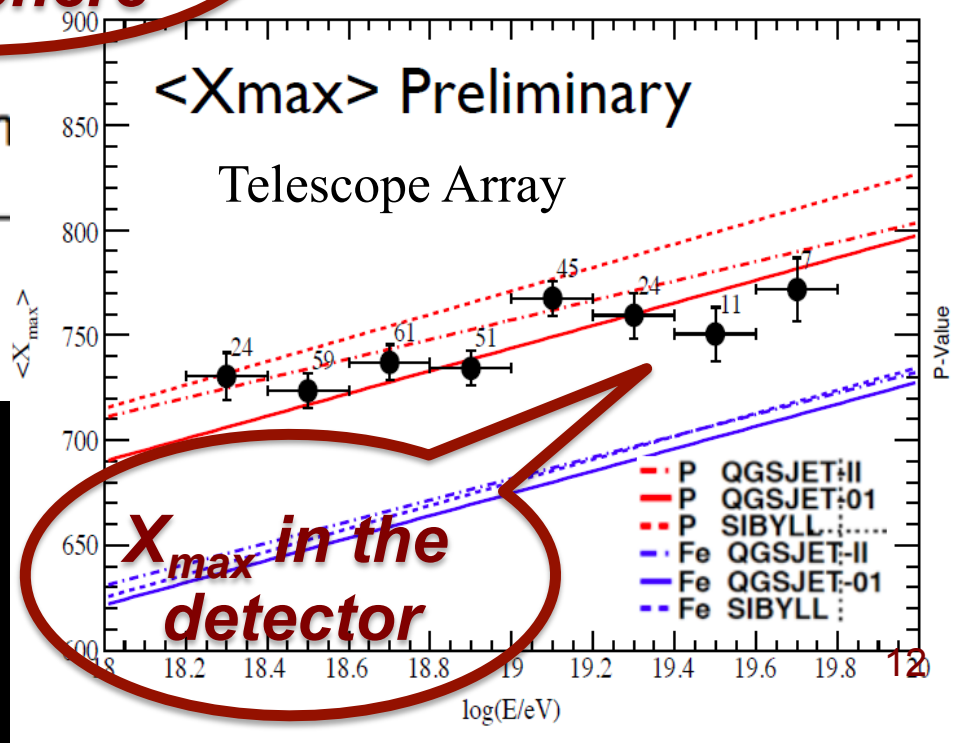




X_{max} in the atmosphere

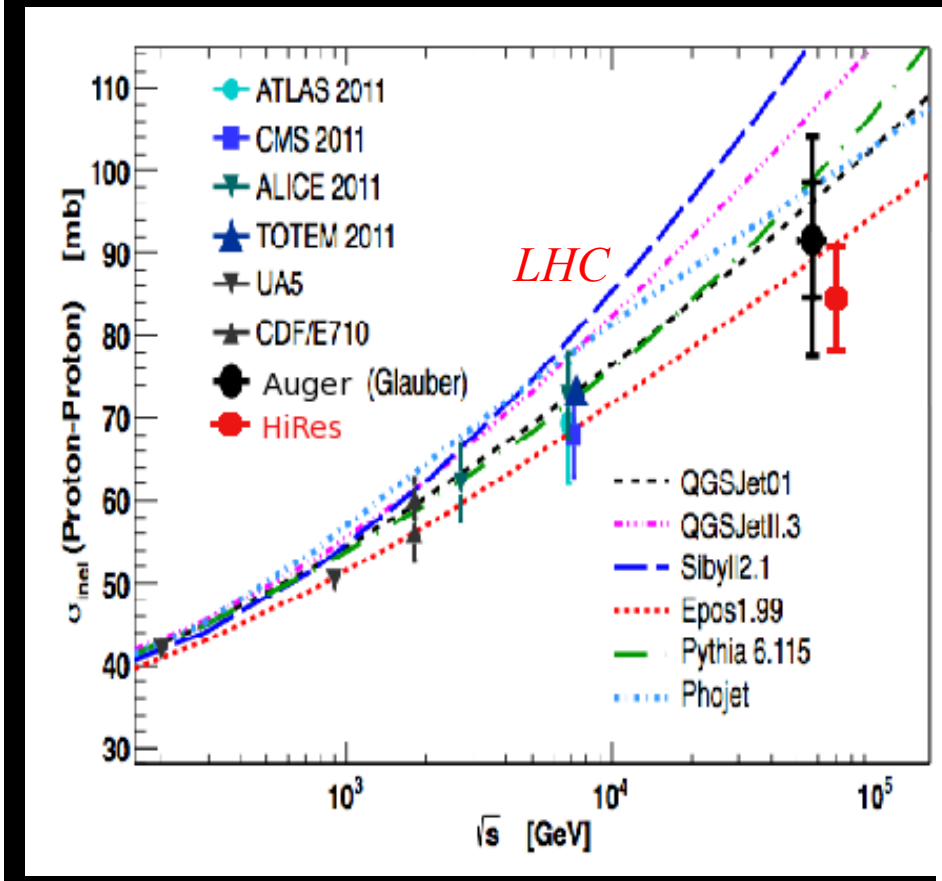
- Auger sees change slope: Change in Composition or interactions

TA: does not confirm



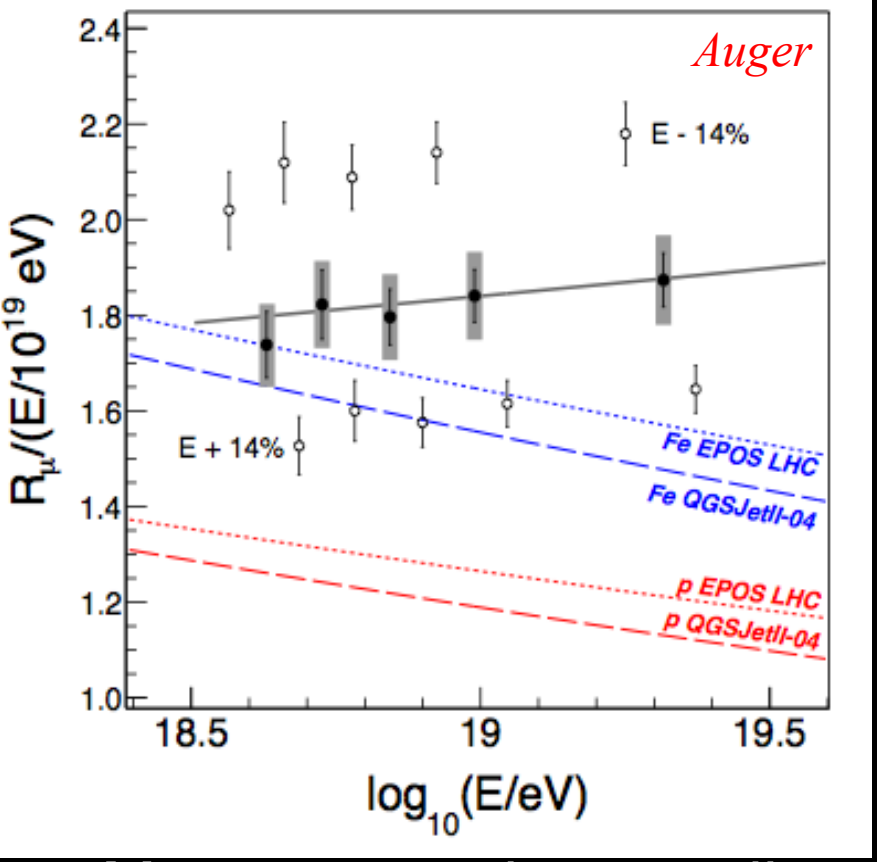
X_{max} in the detector

Explore particle interactions >20 TeV CM



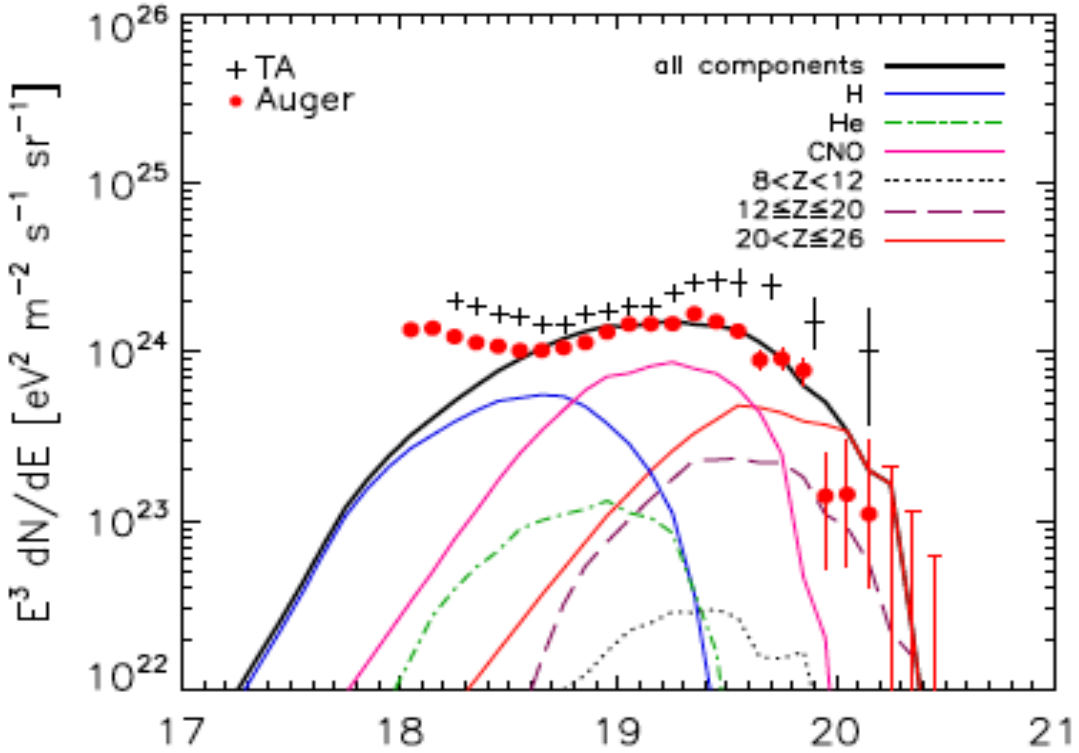
p-p cross section at 57 TeV CM

Inclined showers dominated by muons

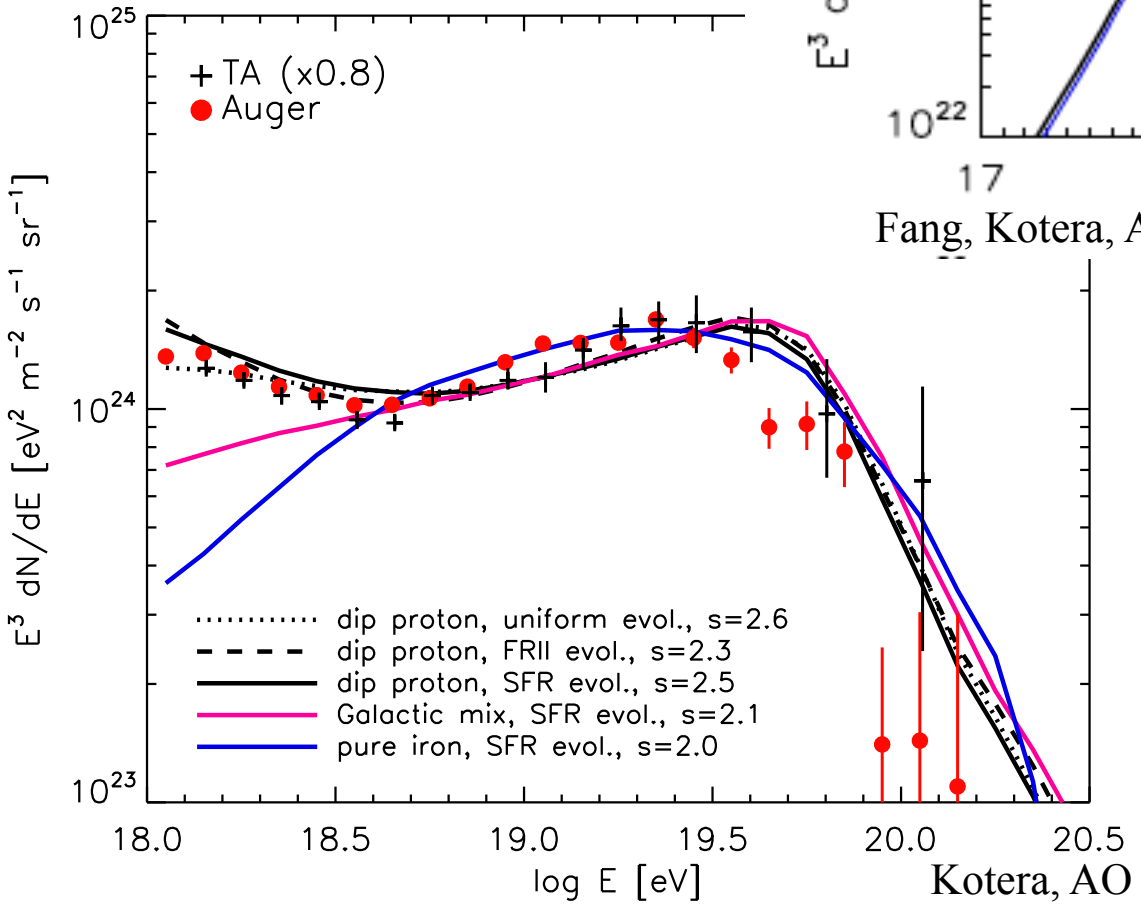


More muons than predicted by hadronic models

GZK or E_{max}?

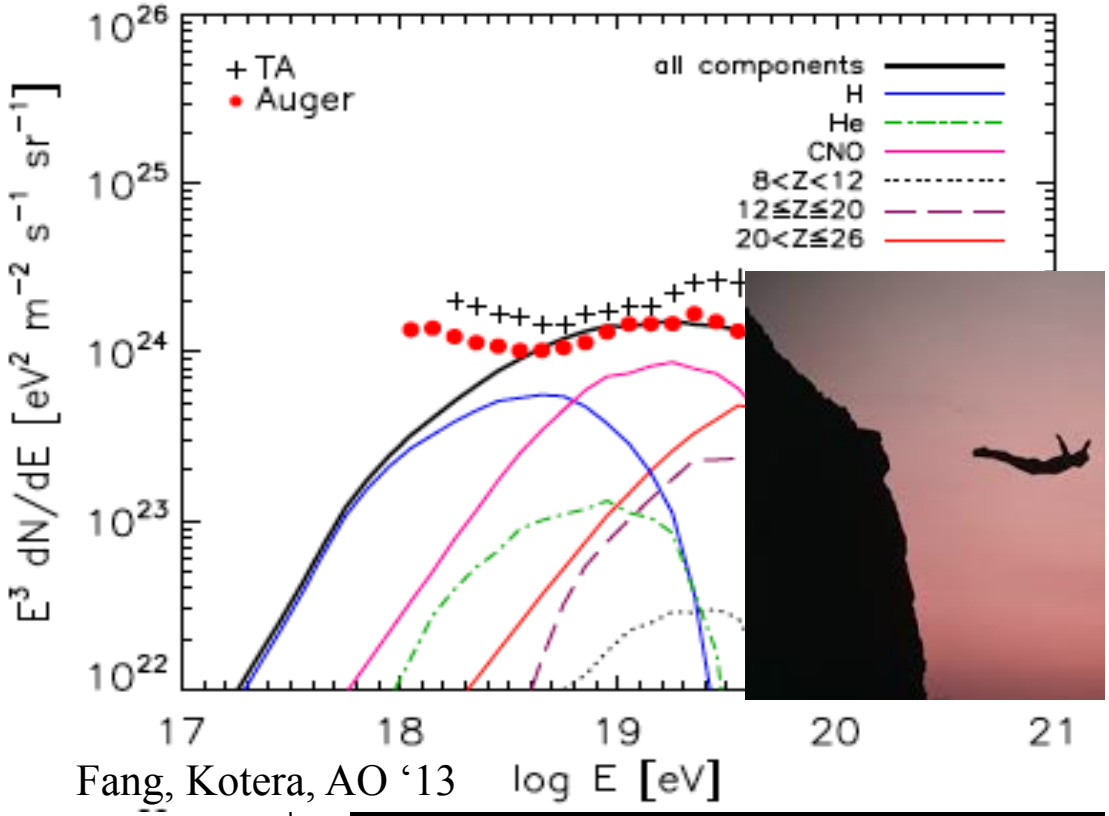


Fang, Kotera, AO '13

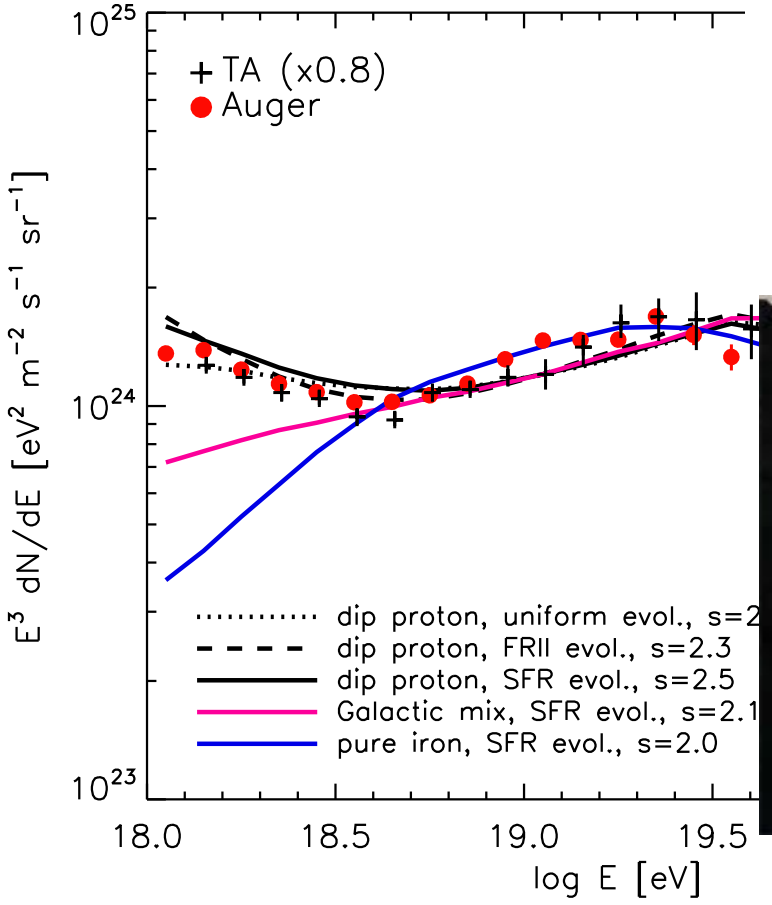


Kotera, AO

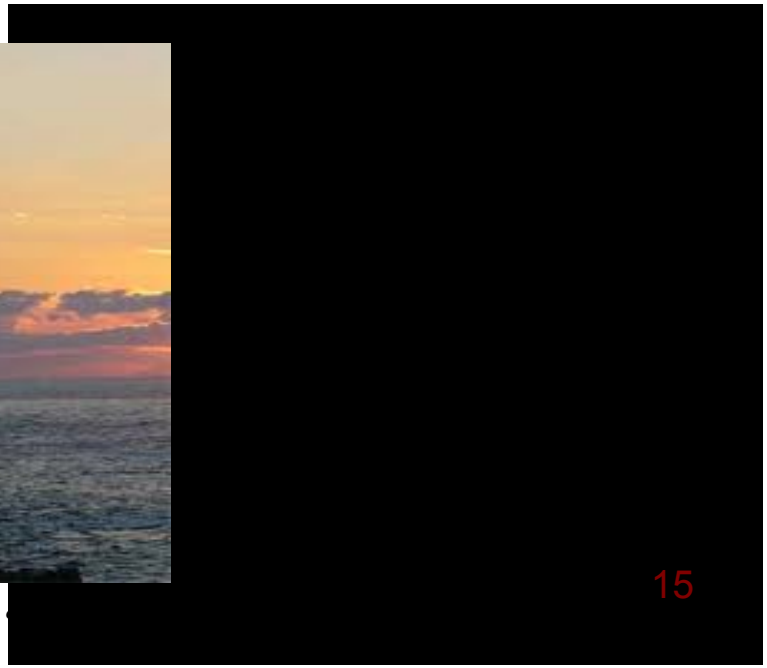
GZK vs E_{max}



Fang, Kotera, AO '13



Kotera, AO



UHECRs Current Status

Leading Observatories: Auger & Telescope Array

Agree on the shape of the spectrum

Energy scale: ~10% difference

Composition: controversial

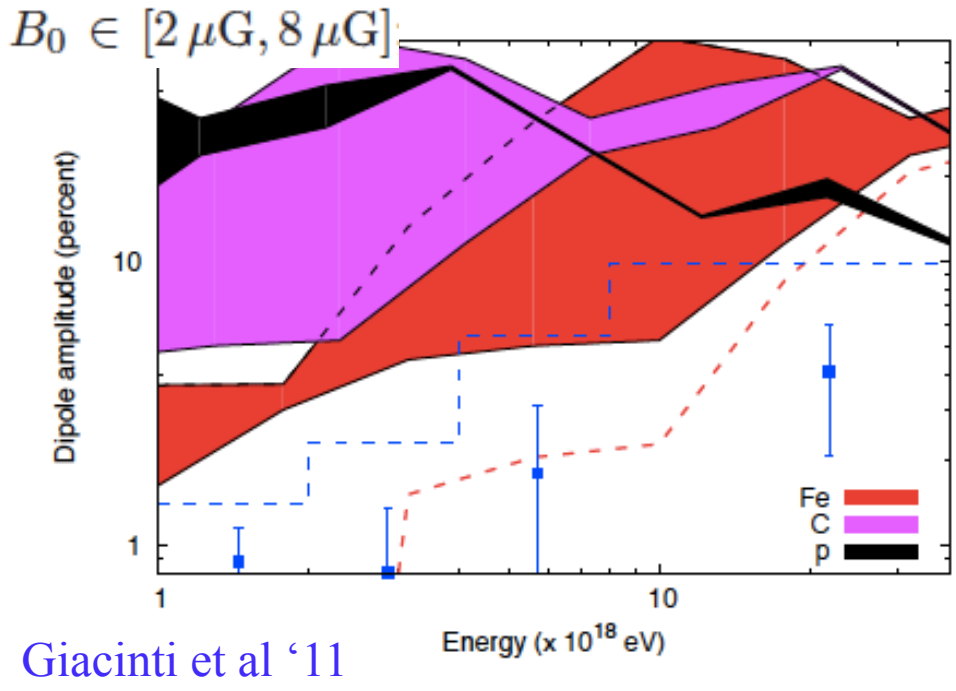
Multi-messenger clues: not yet

Anisotropies?

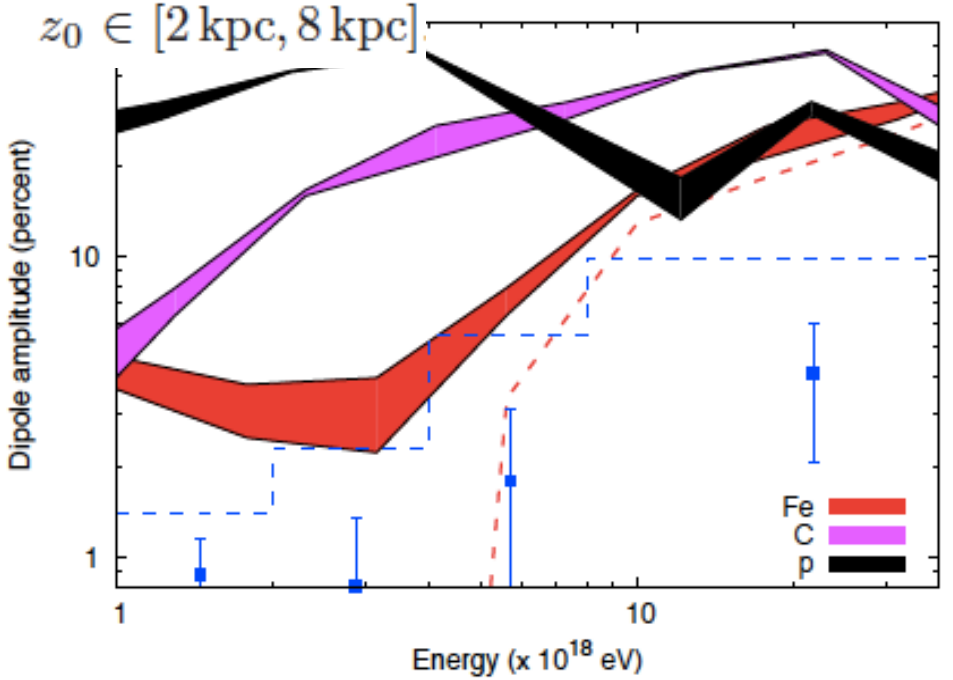
No Galactic Plane Anisotropy

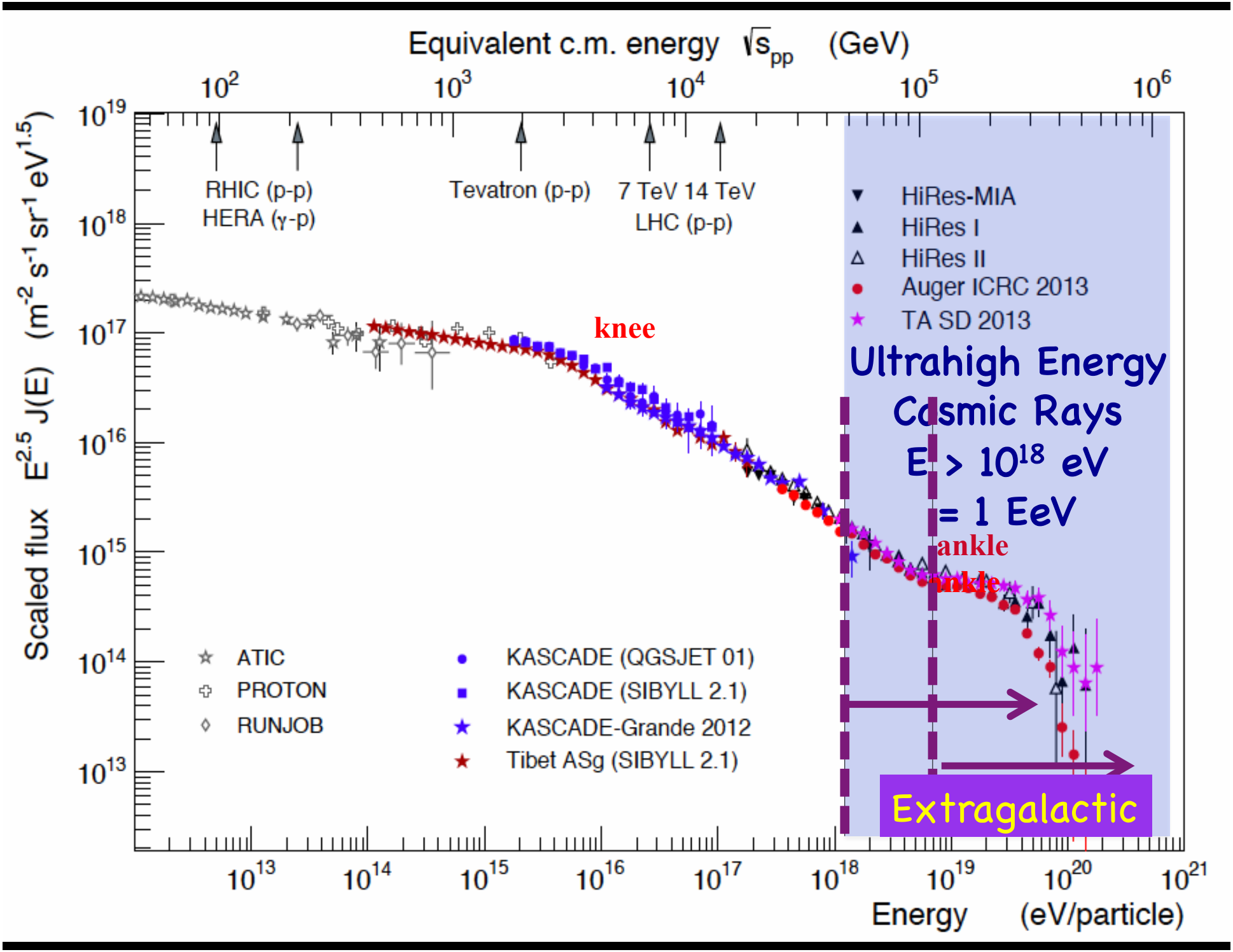
E>20 EeV Cosmic Rays are EXTRAGALACTIC

Auger Anisotropy limits: rule out Galactic protons to CNO as dominant CR component E > 1 EeV and Fe above 20 EeV

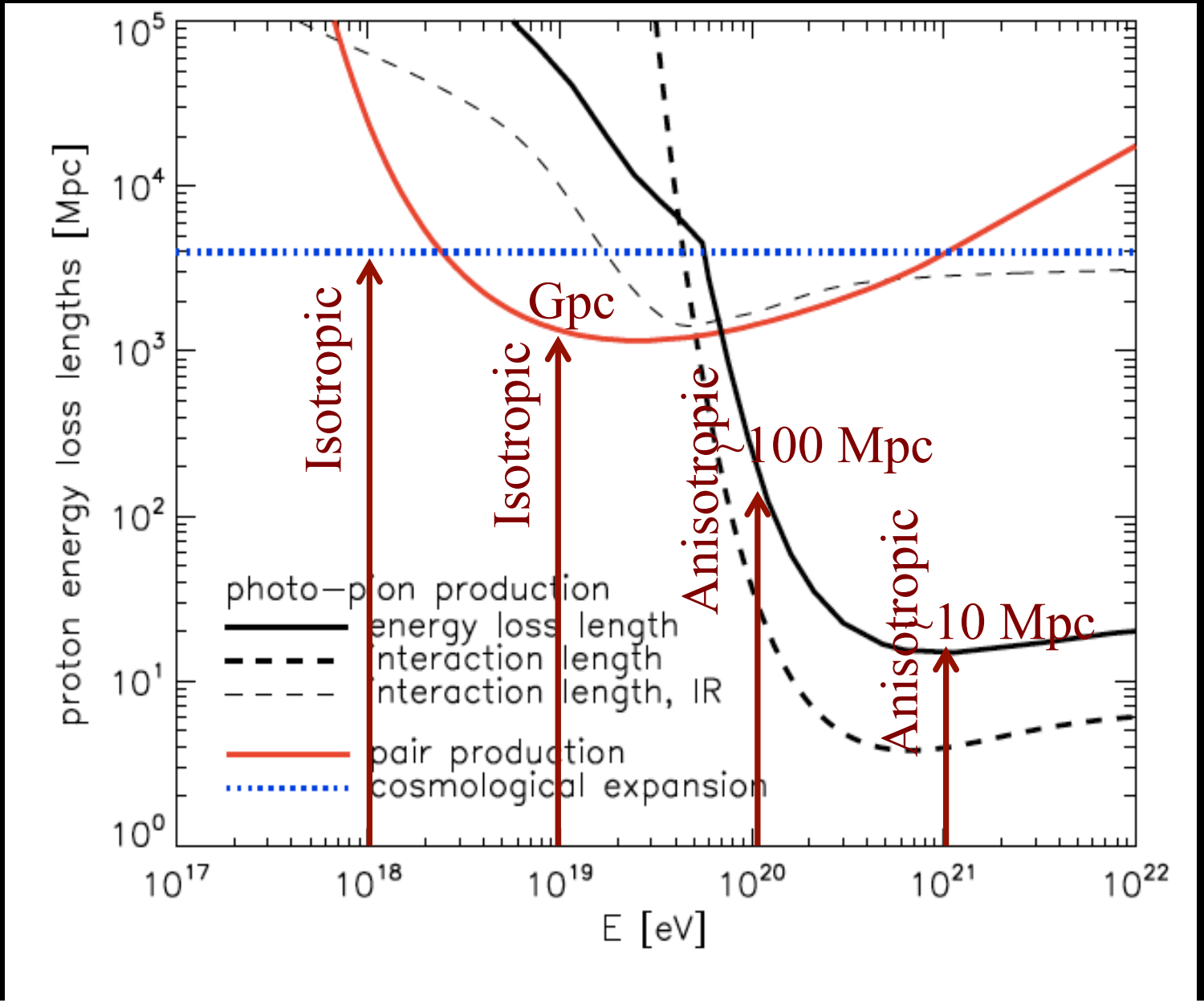


Giacinti et al '11




Equivalent c.m. energy √s_pp (GeV)
10^2
10^3
10^4
10^5
10^6
RHIC (p-p)
HERA (γ-p)
Tevatron (p-p)
7 TeV 14 TeV
LHC (p-p)
HiRes-MIA
HiRes I
HiRes II
Auger ICRC 2013
TA SD 2013
knee
Ultrahigh Energy
Cosmic Rays
E > 10^18 eV
= 1 EeV
ankle
ankle
Extragalactic
Scaled flux E^2.5 J(E) (m^-2 s^-1 sr^-1 eV^1.5)
10^19
10^18
10^17
10^16
10^15
10^14
10^13
ATIC
PROTON
RUNJOB
KASCADE (QGSJET 01)
KASCADE (SIBYLL 2.1)
KASCADE-Grande 2012
Tibet ASg (SIBYLL 2.1)
10^13
10^14
10^15
10^16
10^17
10^18
10^19
10^20
10^21
Energy (eV/particle)

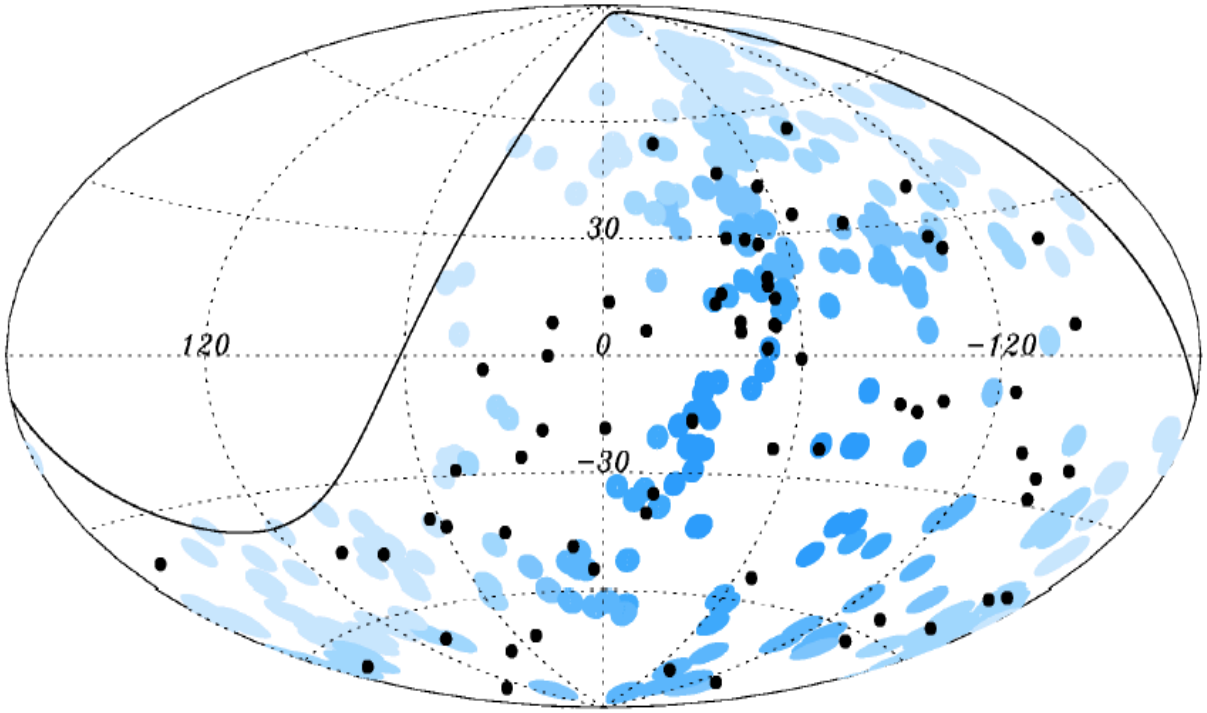
Greisen-Zatsepin-Kuzmin effect

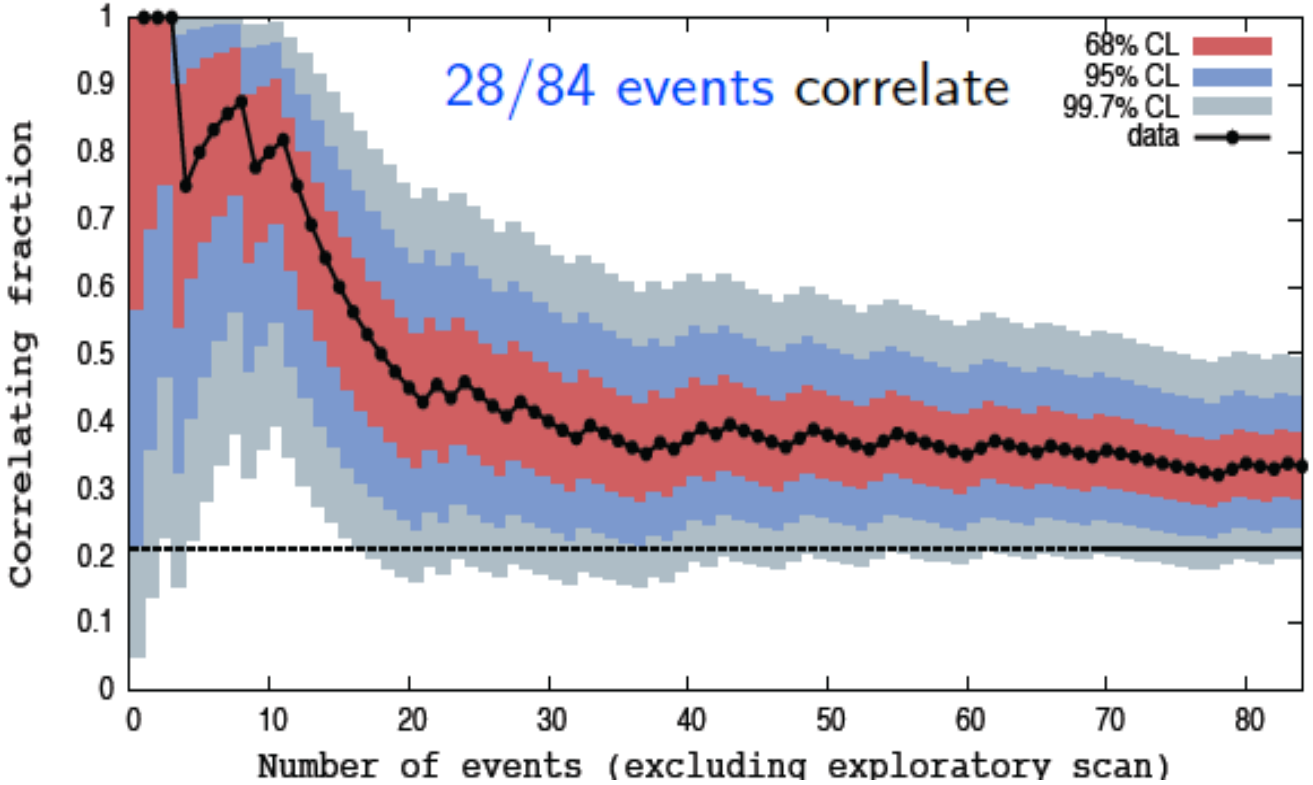


Auger: consistent with Anisotropy

> 60 EeV

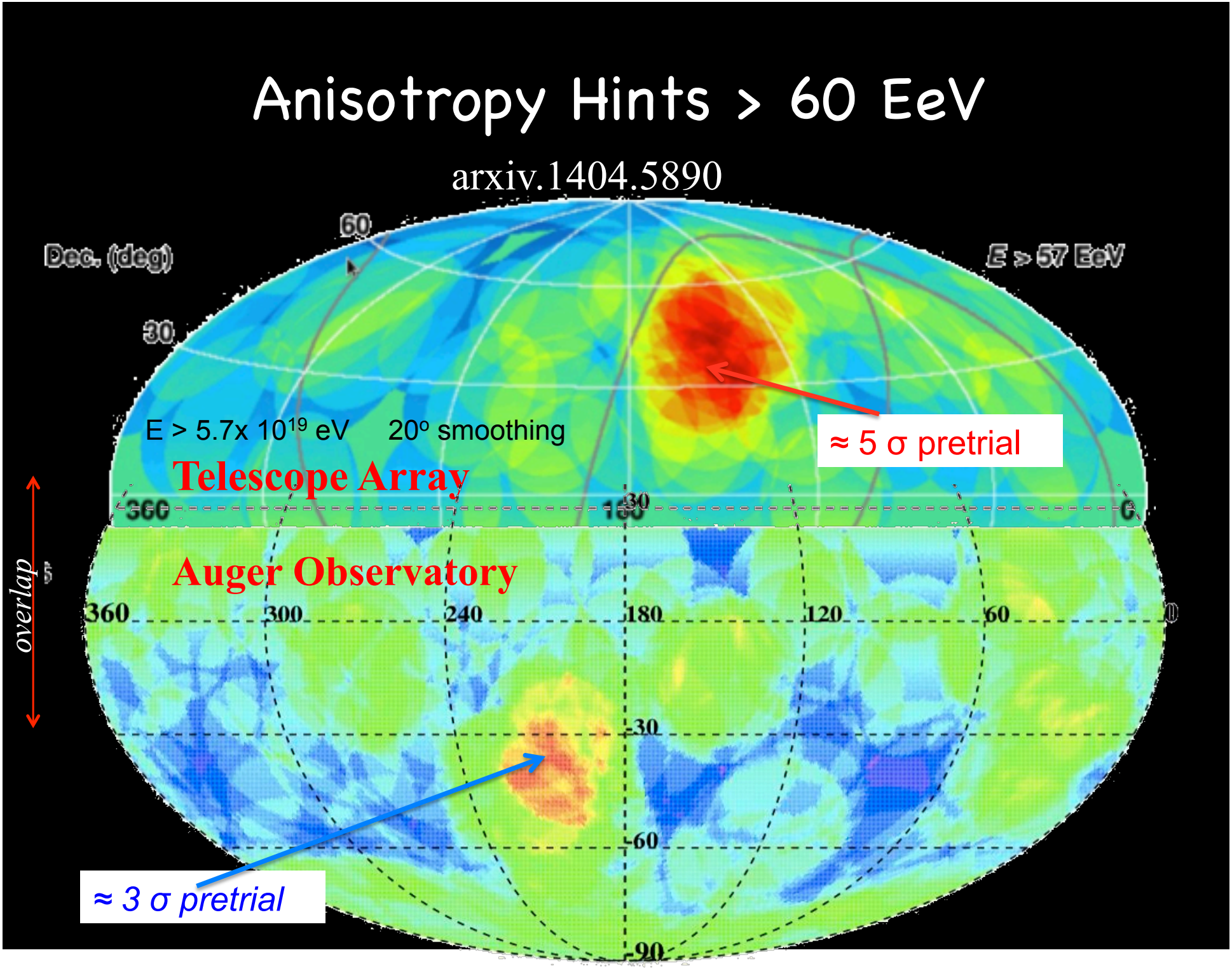
AGN catalog test

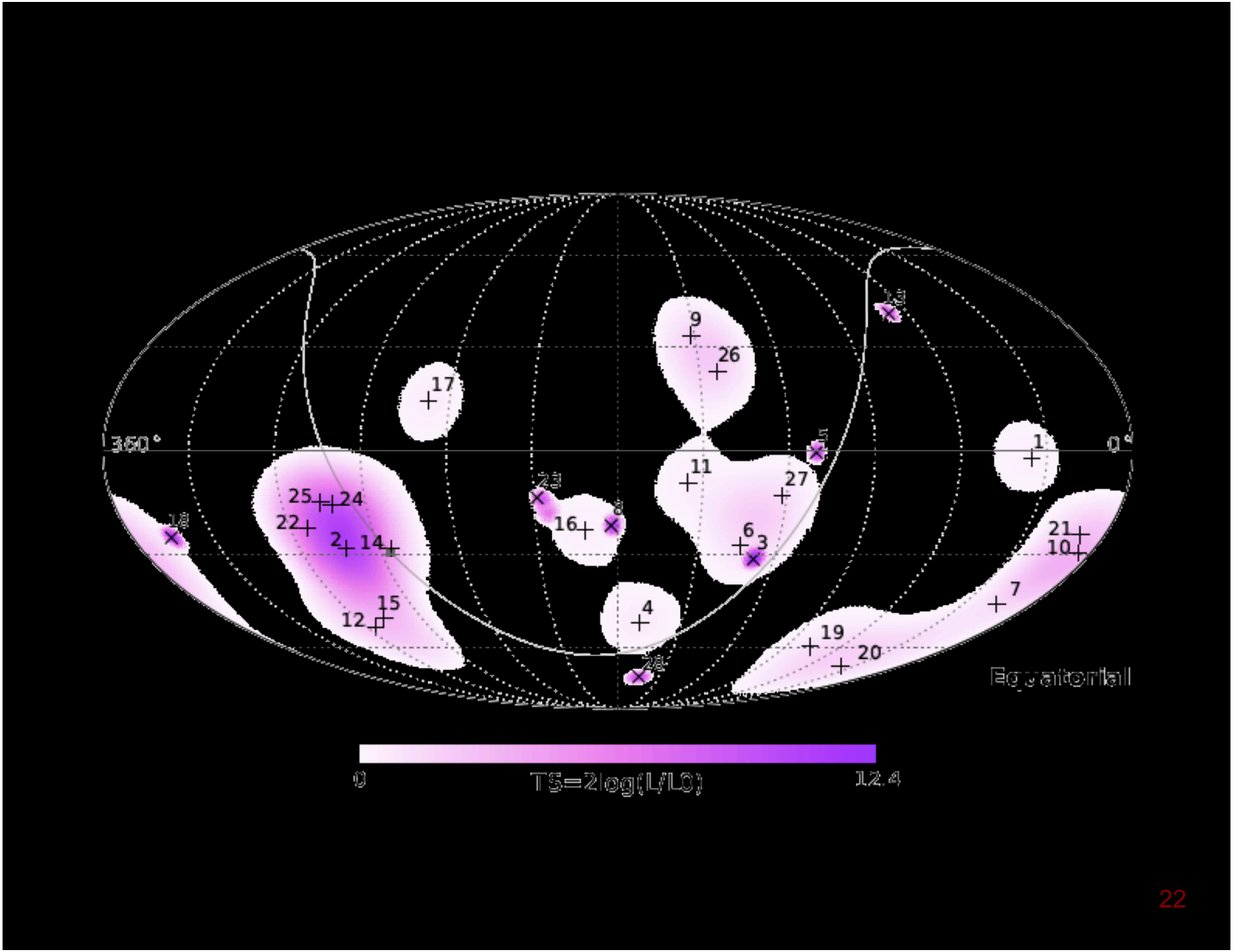




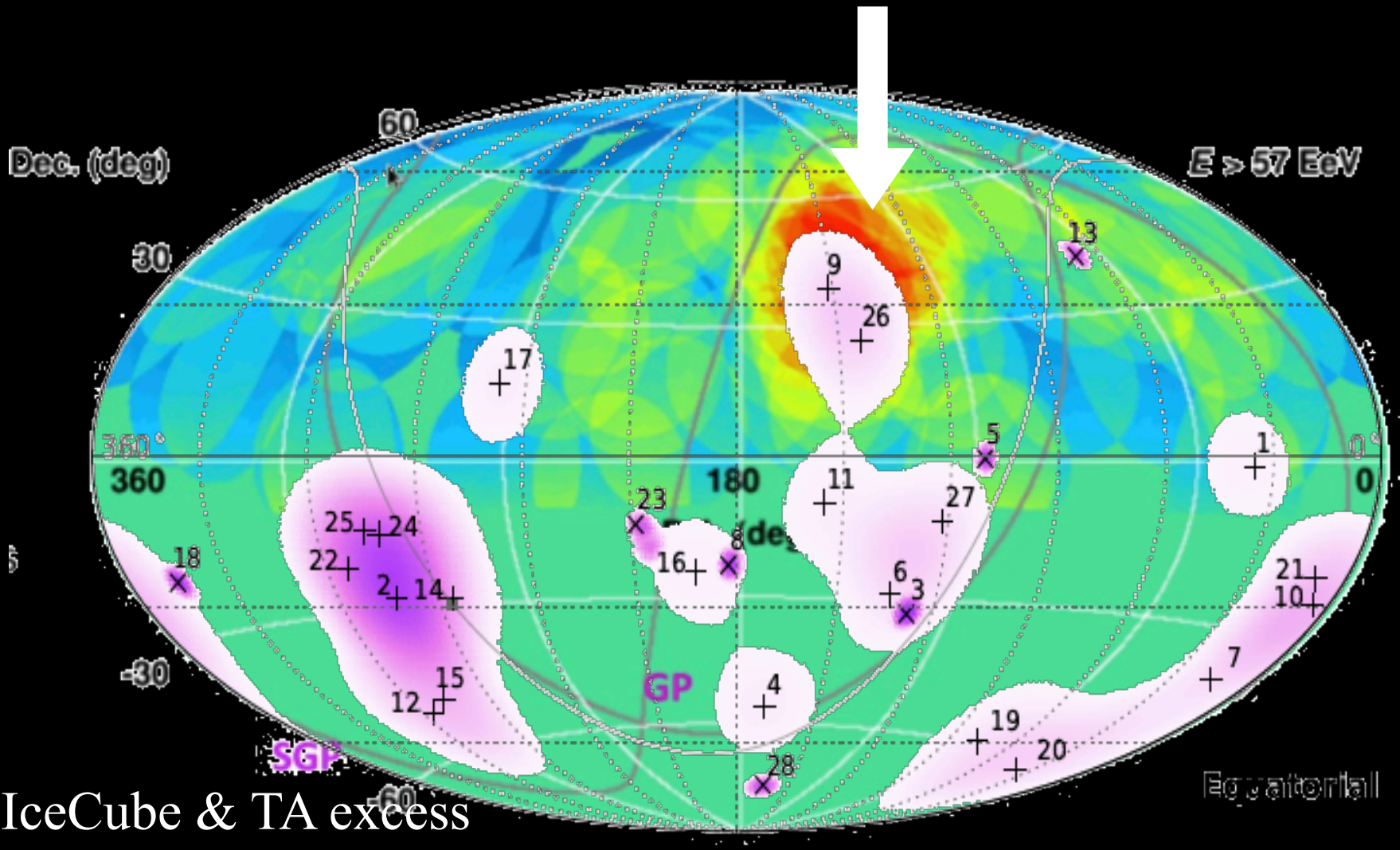
Anisotropy Hints > 60 EeV

arxiv.1404.5890




360°
0°
9
26
17
1
11
27
25
24
22
2
14
16
6
3
21
10
7
4
15
12
19
20
Equatorial
0
TS=2log(L/L0)
12.4

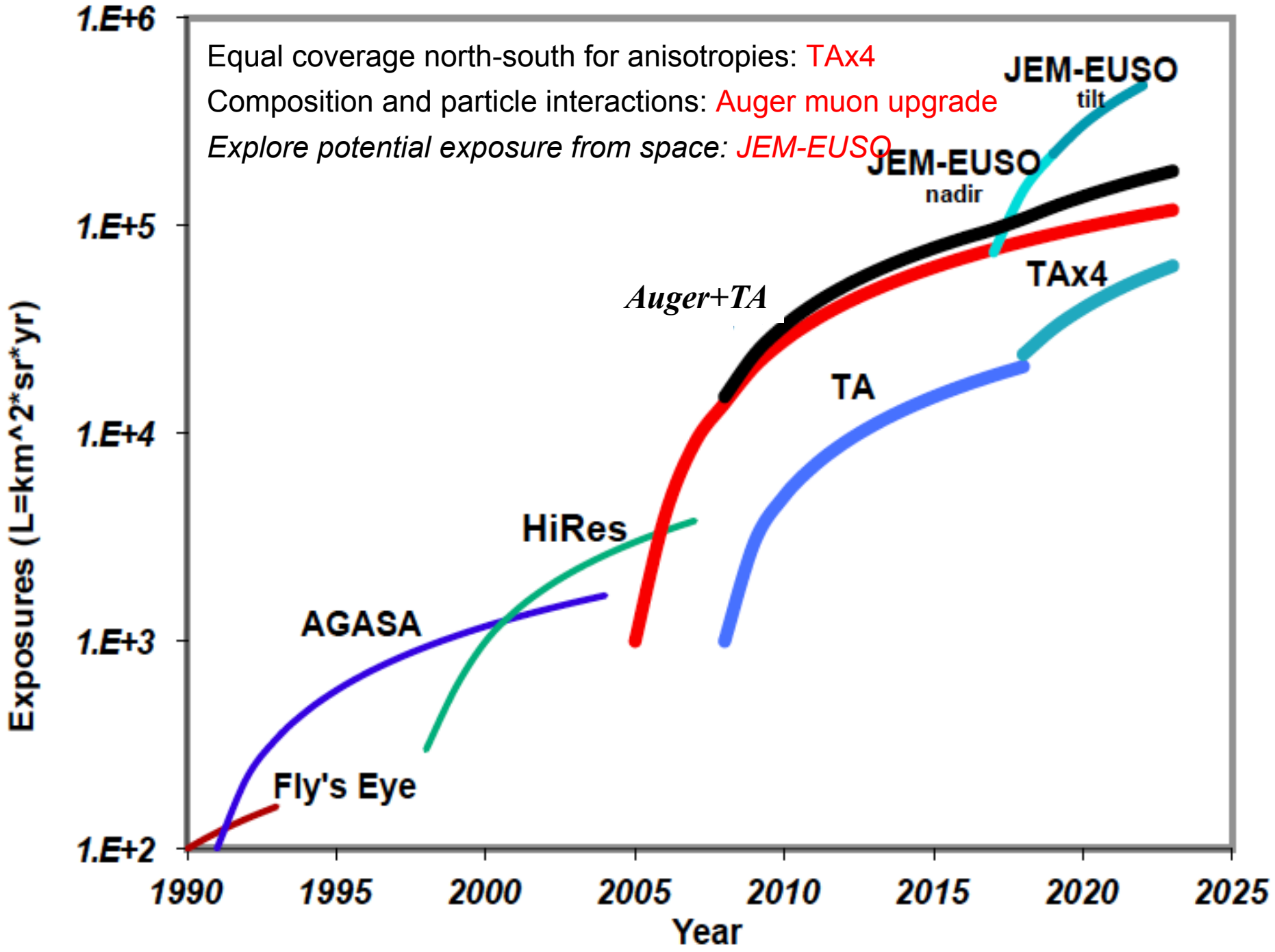
Neutrino & UHECR Coincidence



IceCube & TA excess
overlap signif ~ 2σ
arXiv:1404.6237

Anisotropy Hints > 60 EeV

Statistically limited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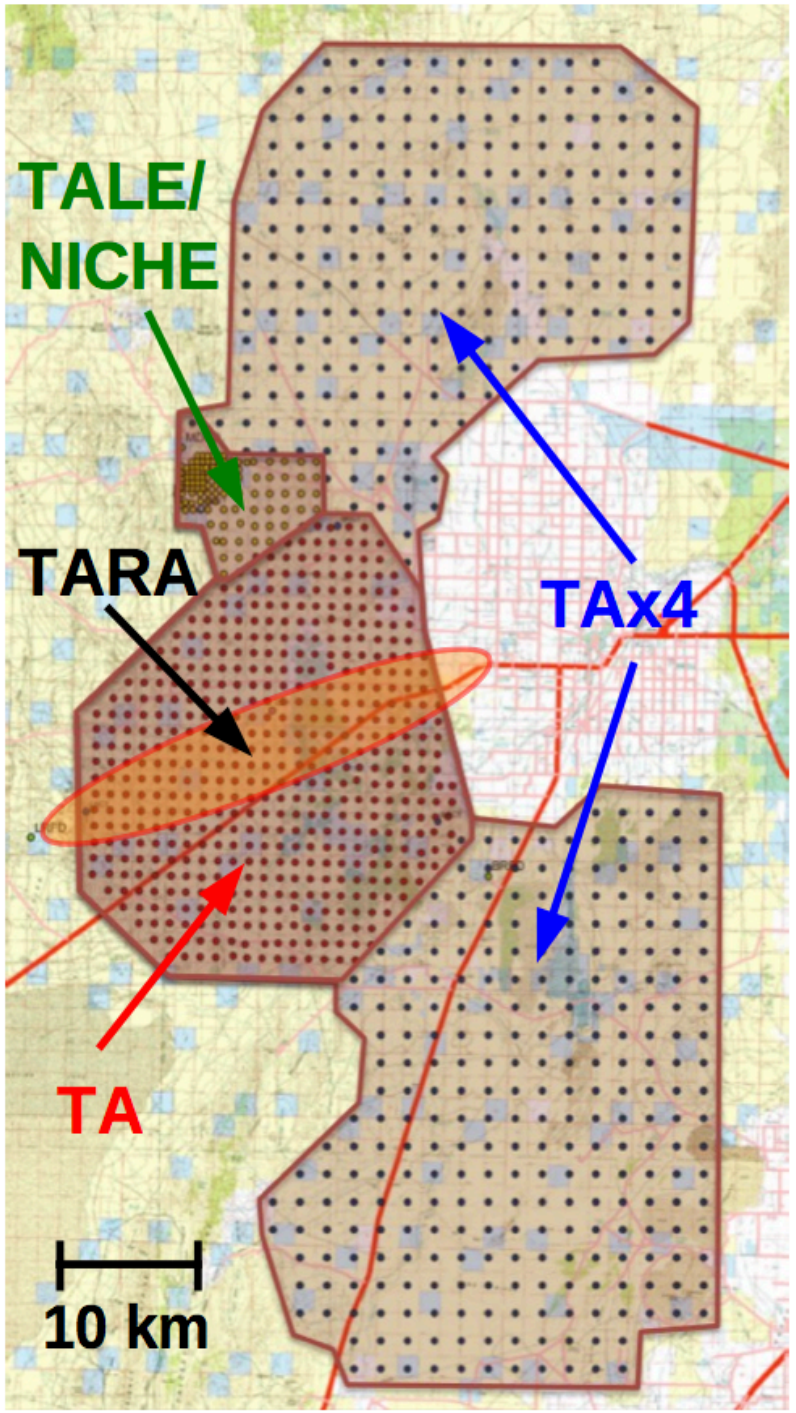
Explore potential exposure from space: JEM-EUSO
JEM-EUSO
tilt
JEM-EUSO
nadir
TAx4
Auger+TA
TA
HiRes
AGASA
Fly's Eye
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year

Telescope Array Expansion

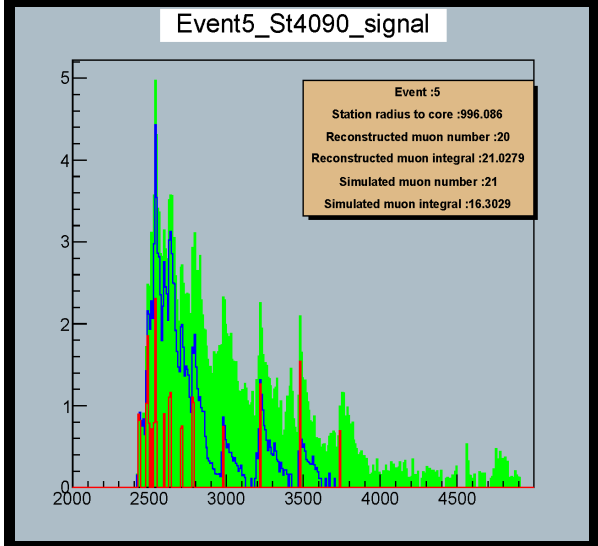
- **Telescope Array** (700 km^2)
  - 507 Surface Detectors; 1.2 km grid.
  - 3 Fluorescence Detectors
- **TALE** (Low-Energy Extension)
  - 100 SD infill array
  - High elevation angle FD
  - Commissioning in progress
- **TARA** Radar R&D
  - 8 MW ERP transmitter at 54 MHz
  - 250 Ms/s VHF receiver
- **TA x 4** (3,000 km^2)
  - 500 new SDs; 2 km grid (Japan, $5M)
  - 1 new FD (US NSF, $1M)
  - Anisotropy: 20 TA years by 2019
- Non Imaging Cherenkov Array **NICHE**
  - TA/TALE 3×10^{16} – 3×10^{20} eV
  - NICHE 10^{15} – 10^{18} eV
  - 85 Cherenkov light collectors
  - Observe shower from 1st interaction
  - Calibrate NICHE with TALE



Pierre Auger Observatory Upgrades:

Target: Better measurement of muons

- **Accelerator maximum** heavier nuclei at high energy
- **Photon, neutrino identification**
- **Proton identification:** astronomy
- **Hadron physics**



1. ***Faster electronics*** *– distinguish muon spikes in SD traces*
2. ***Additional muon detectors*** *– scintillators, RPCs*
3. ***Modified SD*** *– segmented tanks*

In the next decade, Auger will roughly triple its present data set: obtaining **event-by-event** composition measurements will be an **order-of-magnitude** increase in that kind of data.

Off the Extreme Energy Cliff

JEM-EUSO

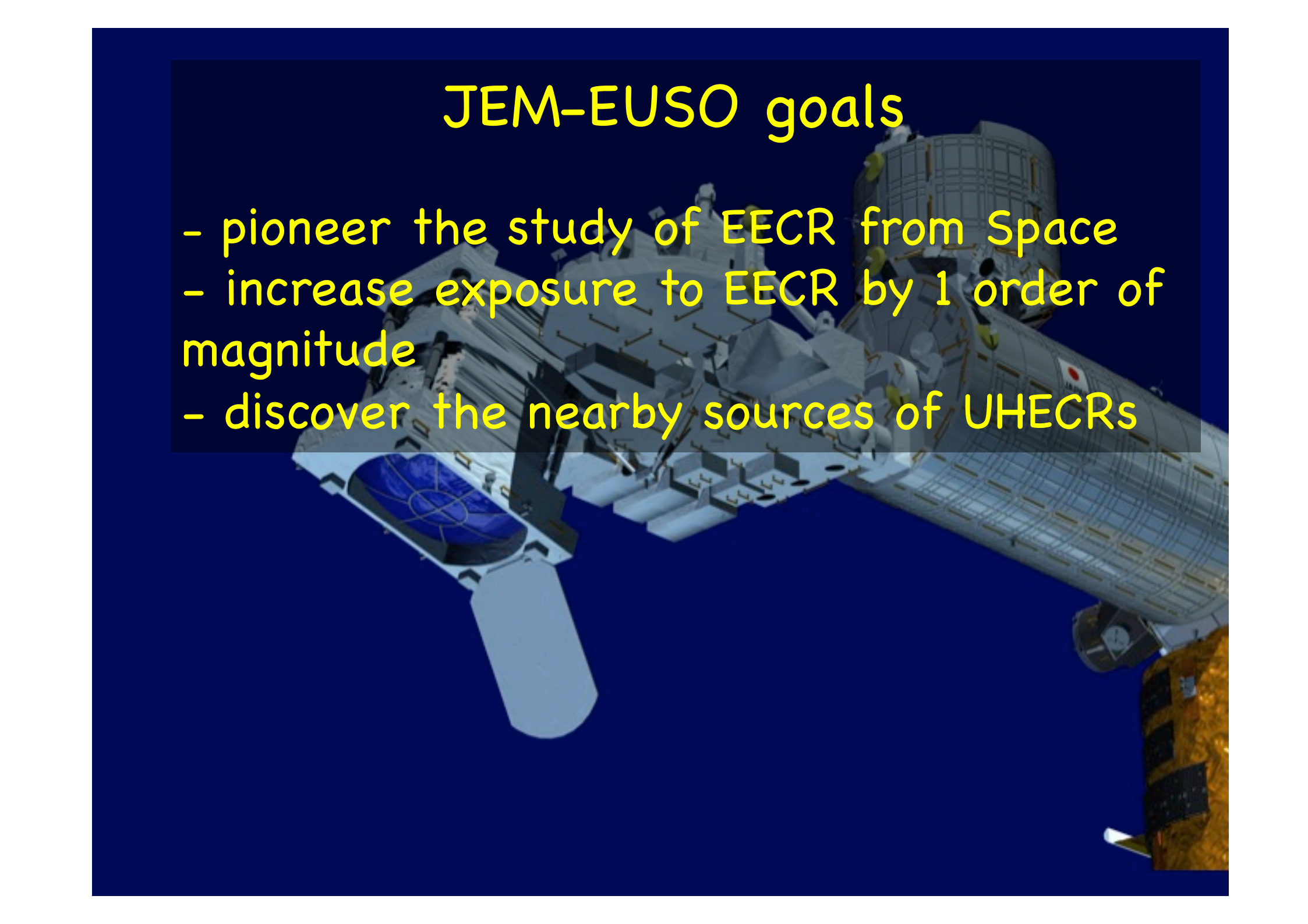
Extreme Universe Space Observatory (EUSO)
in the Japanese Experiment Module (JEM)
of the International Space Station (ISS)

Japan, USA, Korea, Mexico, Russia, Algeria
Europe: Bulgaria, France, Germany, Italy,
Poland, Slovakia, Spain, Switzerland, Sweden
15 Countries, 300 researchers
Leading institution: RIKEN

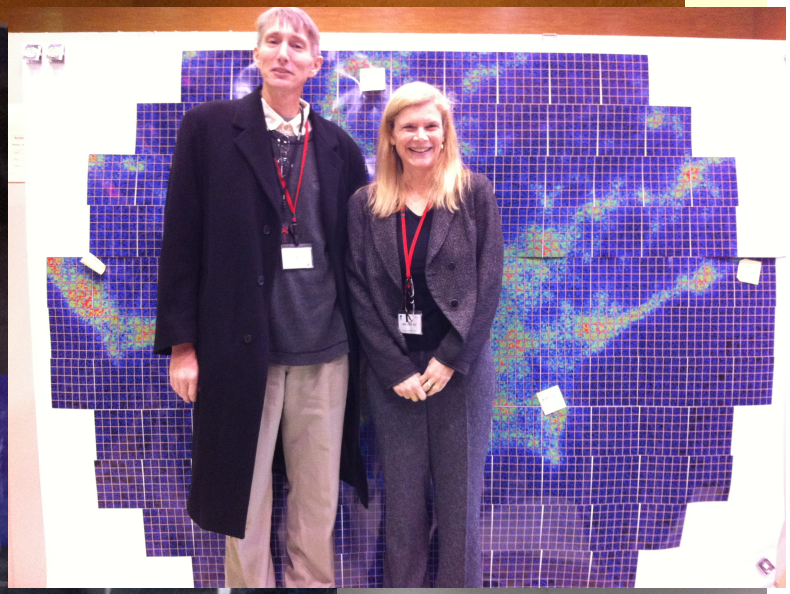
PI: Piergiorgio Picozza

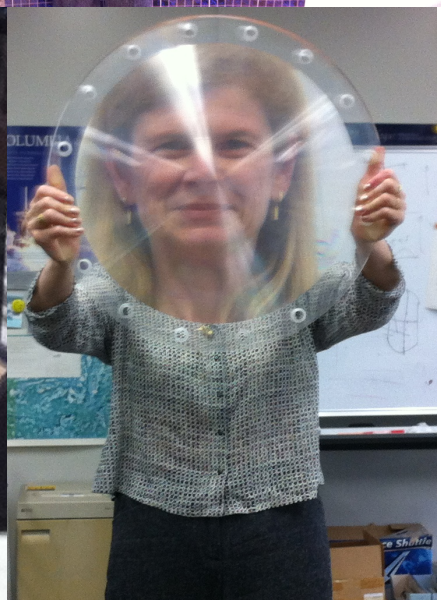
JEM-EUSO goals

- pioneer the study of EECR from Space
- increase exposure to EECR by 1 order of magnitude
- discover the nearby sources of UHECRs



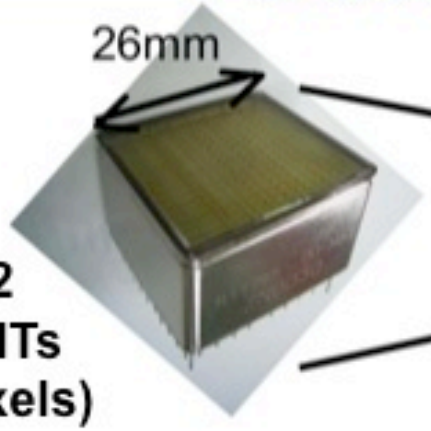
Science Instrument



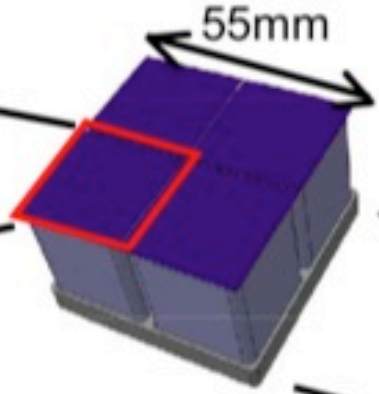


Focal Surface Detector

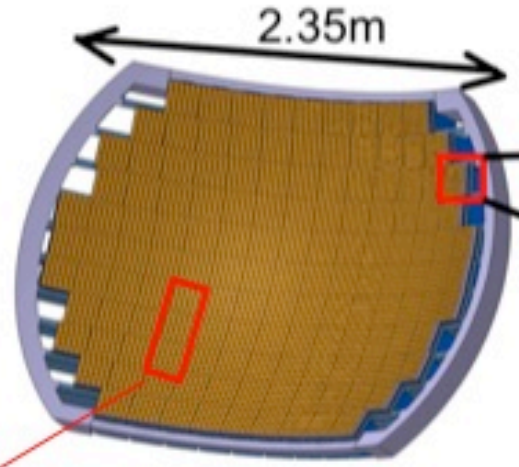
Y. Kawasaki, ID 0472
M. Ricci, ID 0335

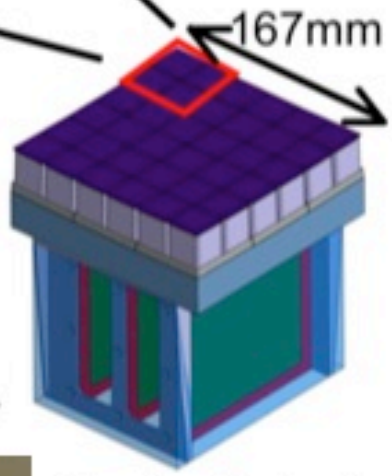


4932 MAPMTs (8x8 pixels)



Elementary Cell (2x2 PMTs = 256 pixels)





Focal Surface detector
137 PDMs
= 0.3M Pixels

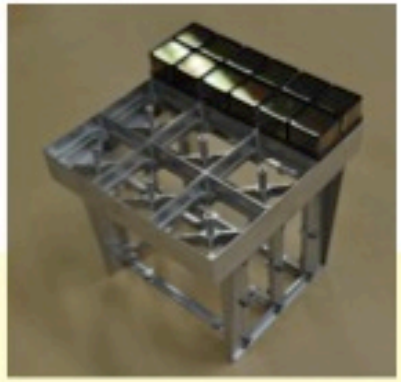
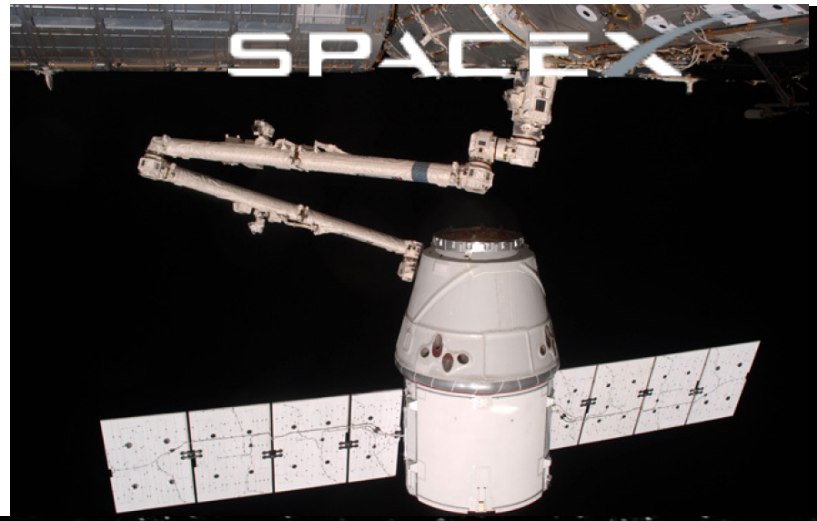
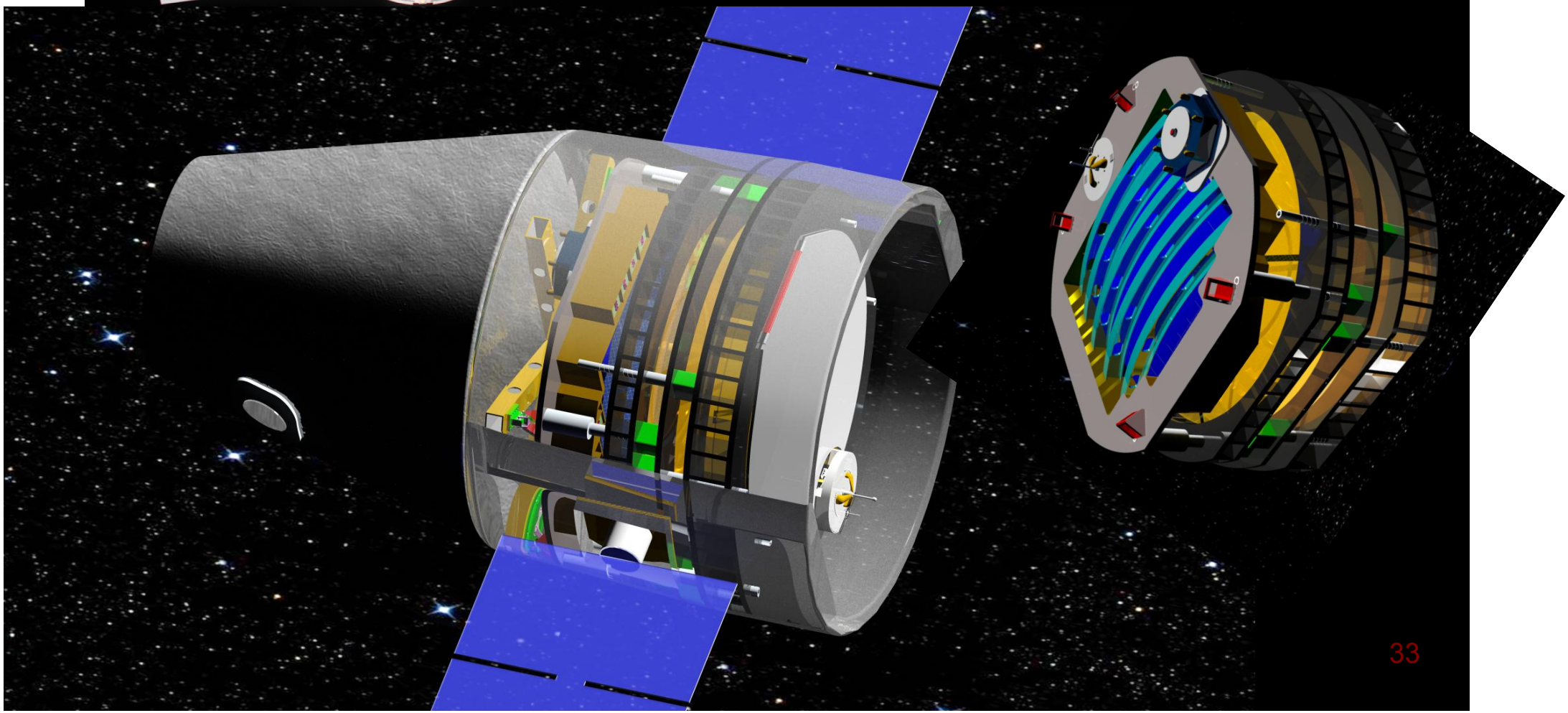


Photo-Detector Module (3x3 ECs = 2,304 pixels)

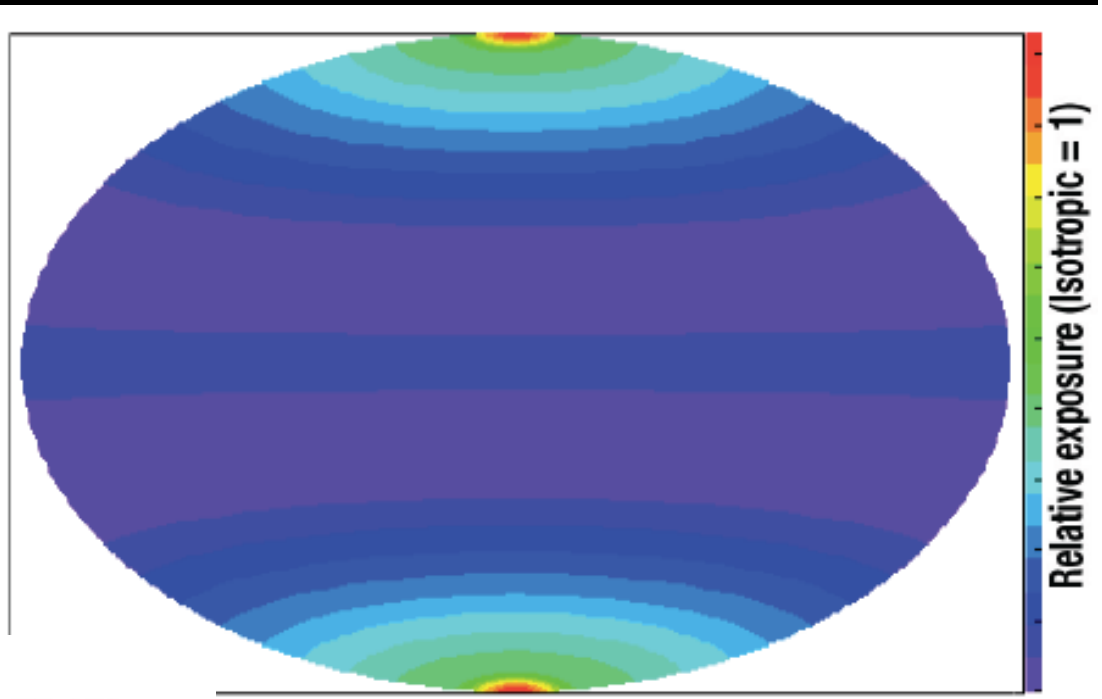
1 High Voltage / PDM

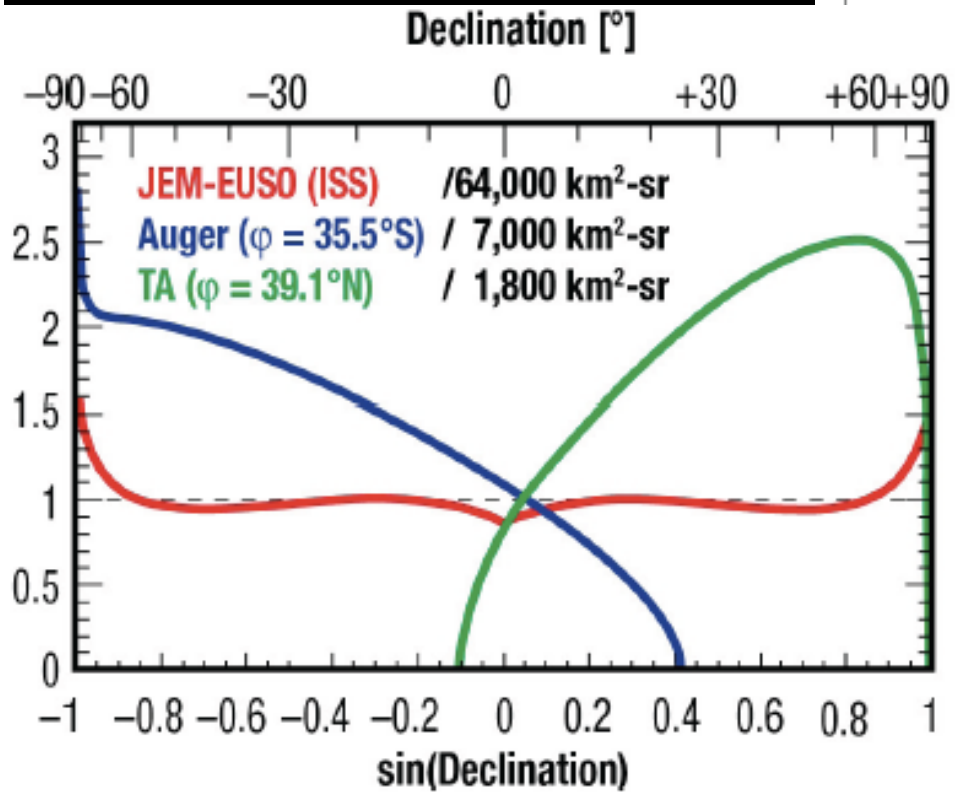

SPACEX


DRAGON

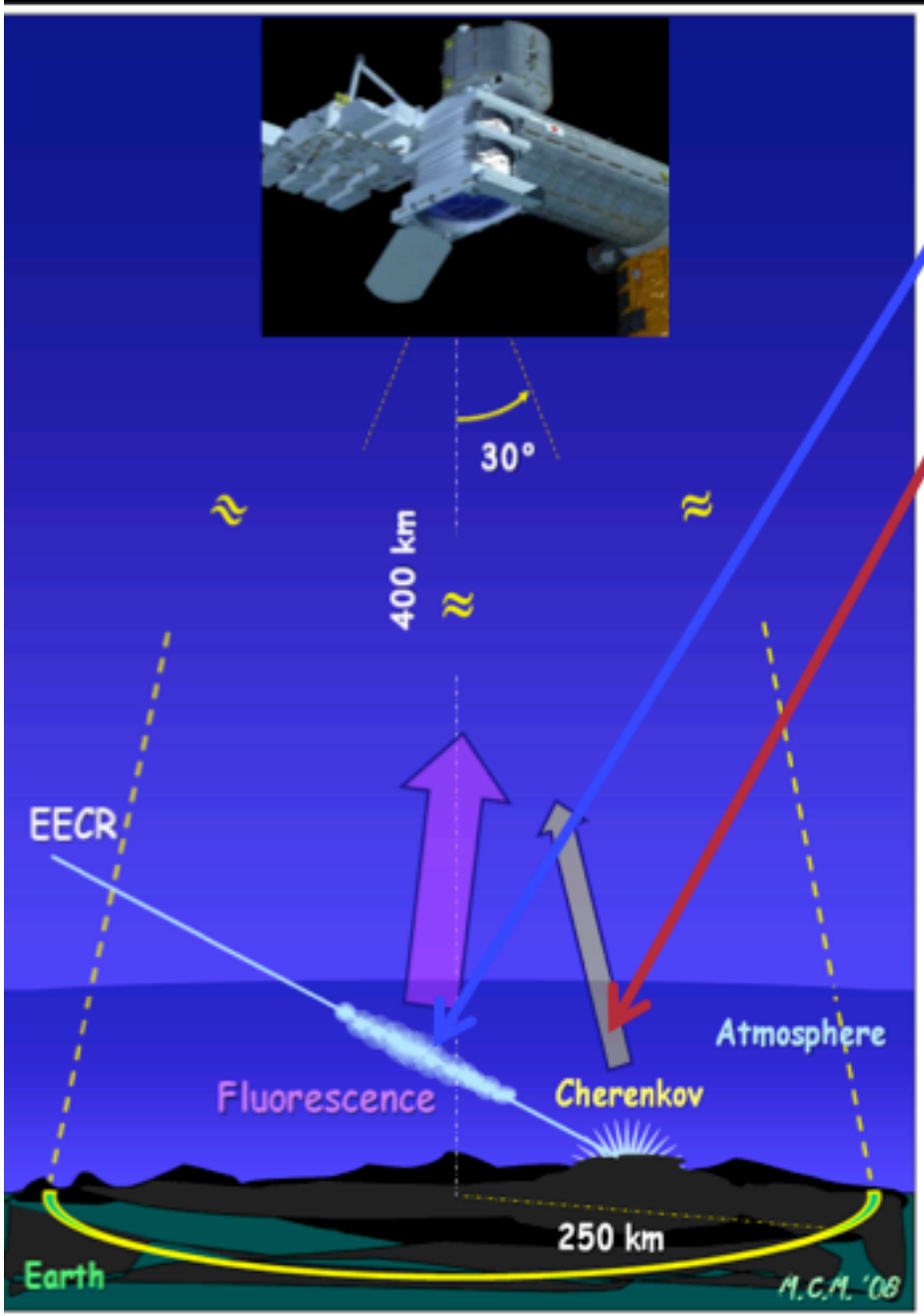


JEM-EUSO
Sky Coverage





Fluorescence from SPACE

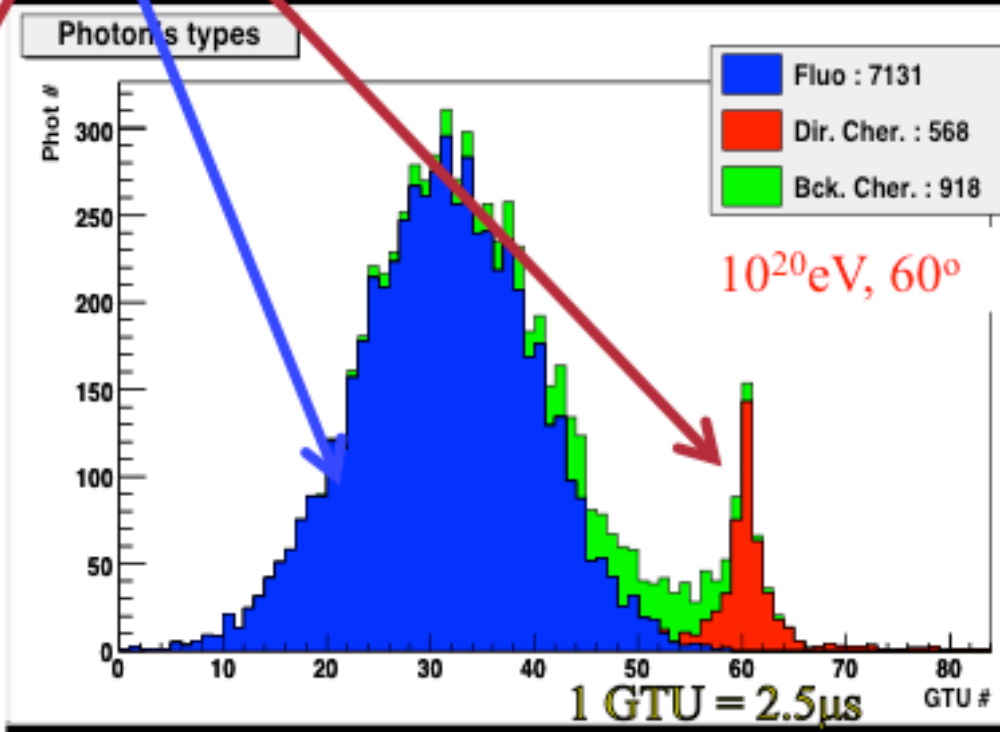


Fast Signal: 50 -150 μs

a) Fluorescence

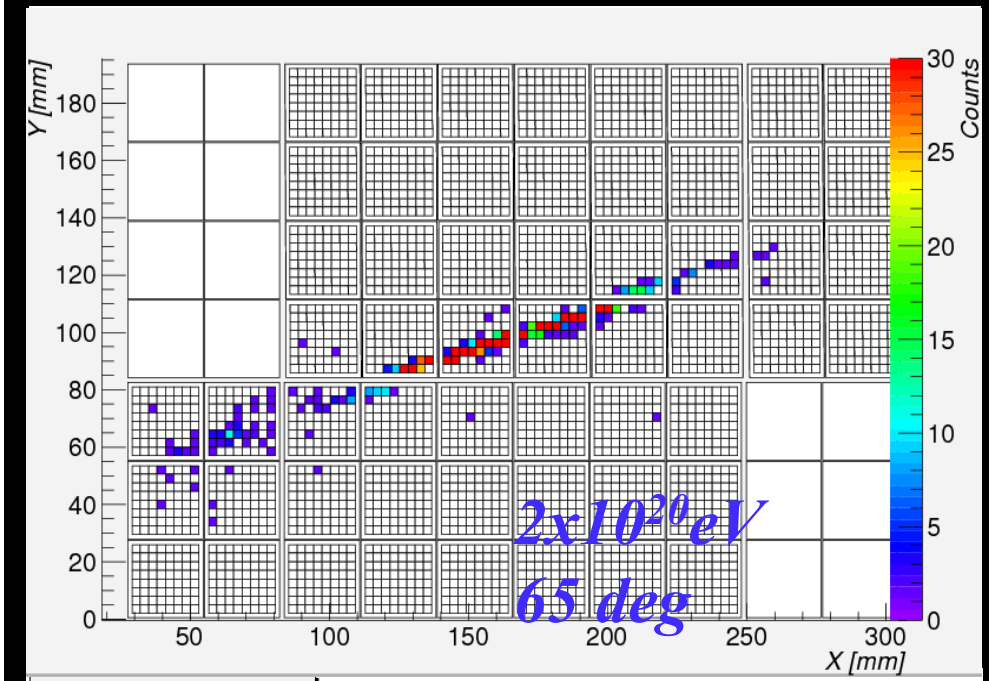
b) Scattered Cherenkov

c) Direct (reflected Cherenkov)

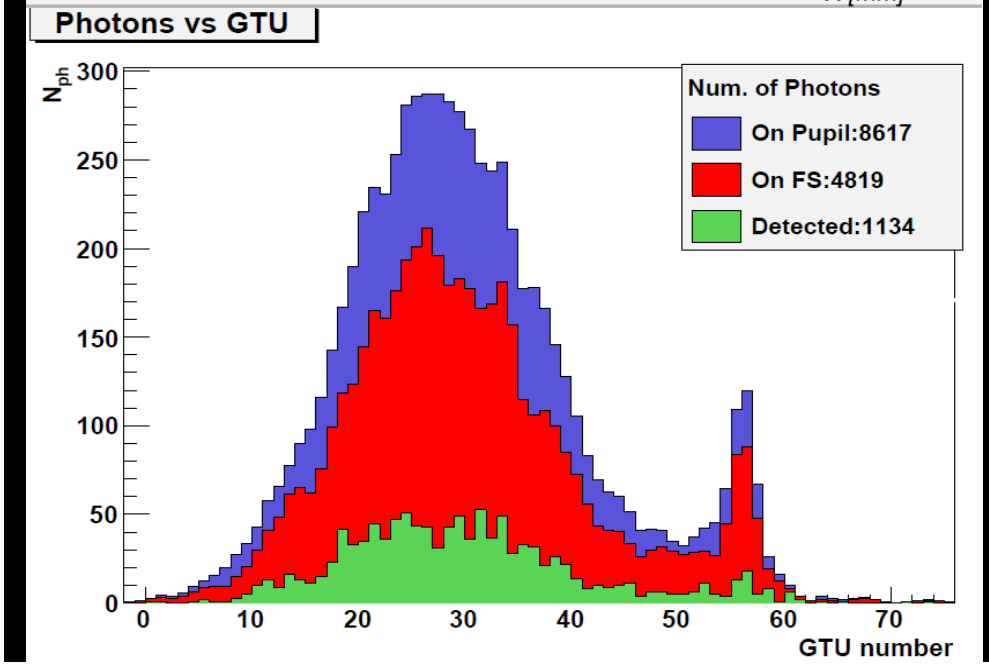


Background: 500 /m^2 sr ns

Shower Simulation

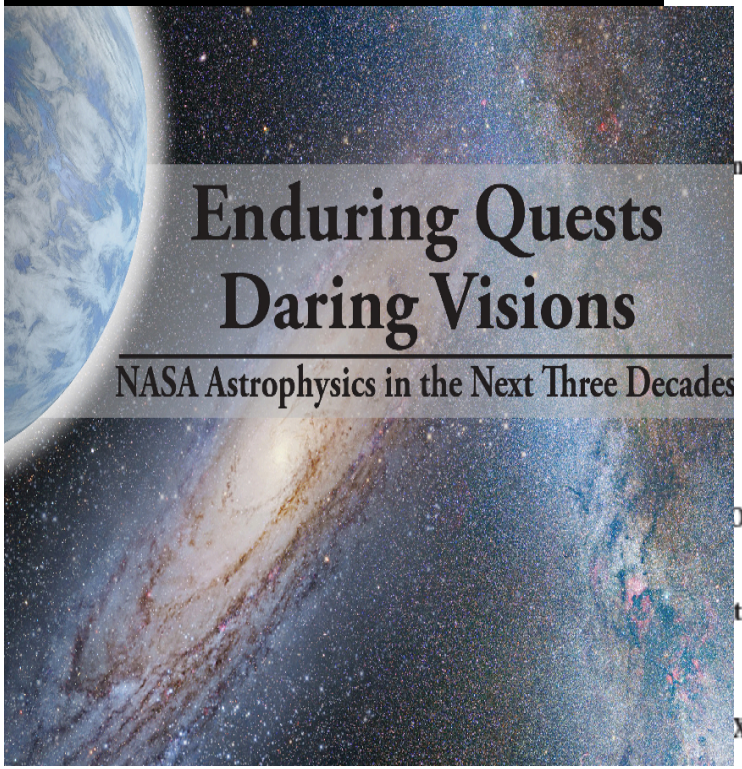


Simulated air shower image on the focal surface detector.



Detected photoelectrons are recorded every Gate Time Unit (GTU) of 2.5μs continuously.

NASA Astrophysics Roadmap 2014

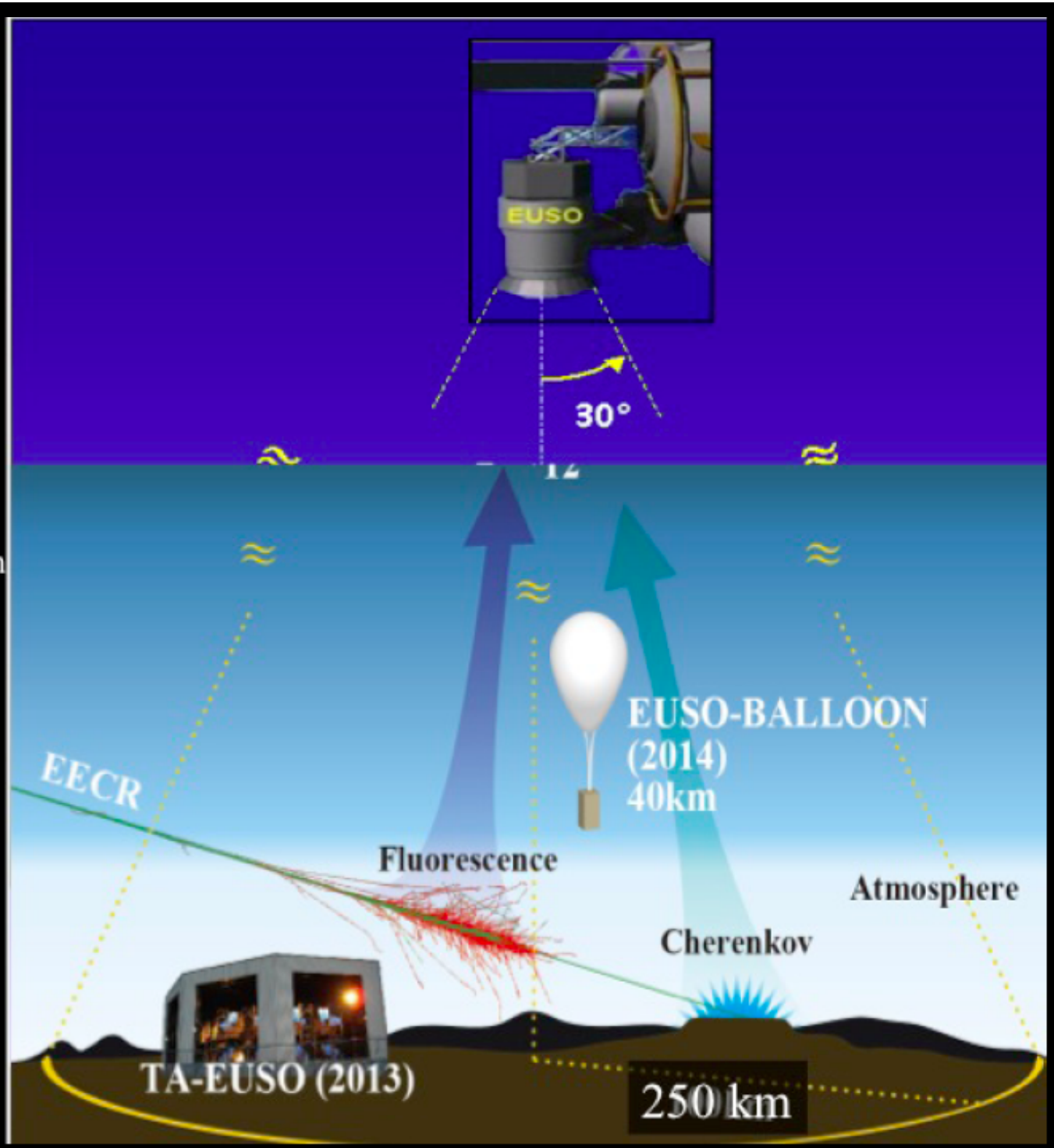


	Near-Term	Formative	Visionary
Gravitational Waves		Gravitational Wave Surveyor	Gravitational Wave Mapper
Cosmic rays	JEM-EUSO		
Radio			Cosmic Dawn Mapper
Microwaves		CMB Polarization Surveyor	
Infrared	JWST	Far IR Surveyor	
Optical	WFIRST-AFTA, Euclid	LUVOIR Surveyor	ExoEarth Mapper
Ultraviolet	TESS, Gaia		
X-rays	NICER, Astro-H	Xray Surveyor	Black Hole Mapper

The EUSO program

1. EUSO-TA:
Ground detector at
Telescope Array site: 2013

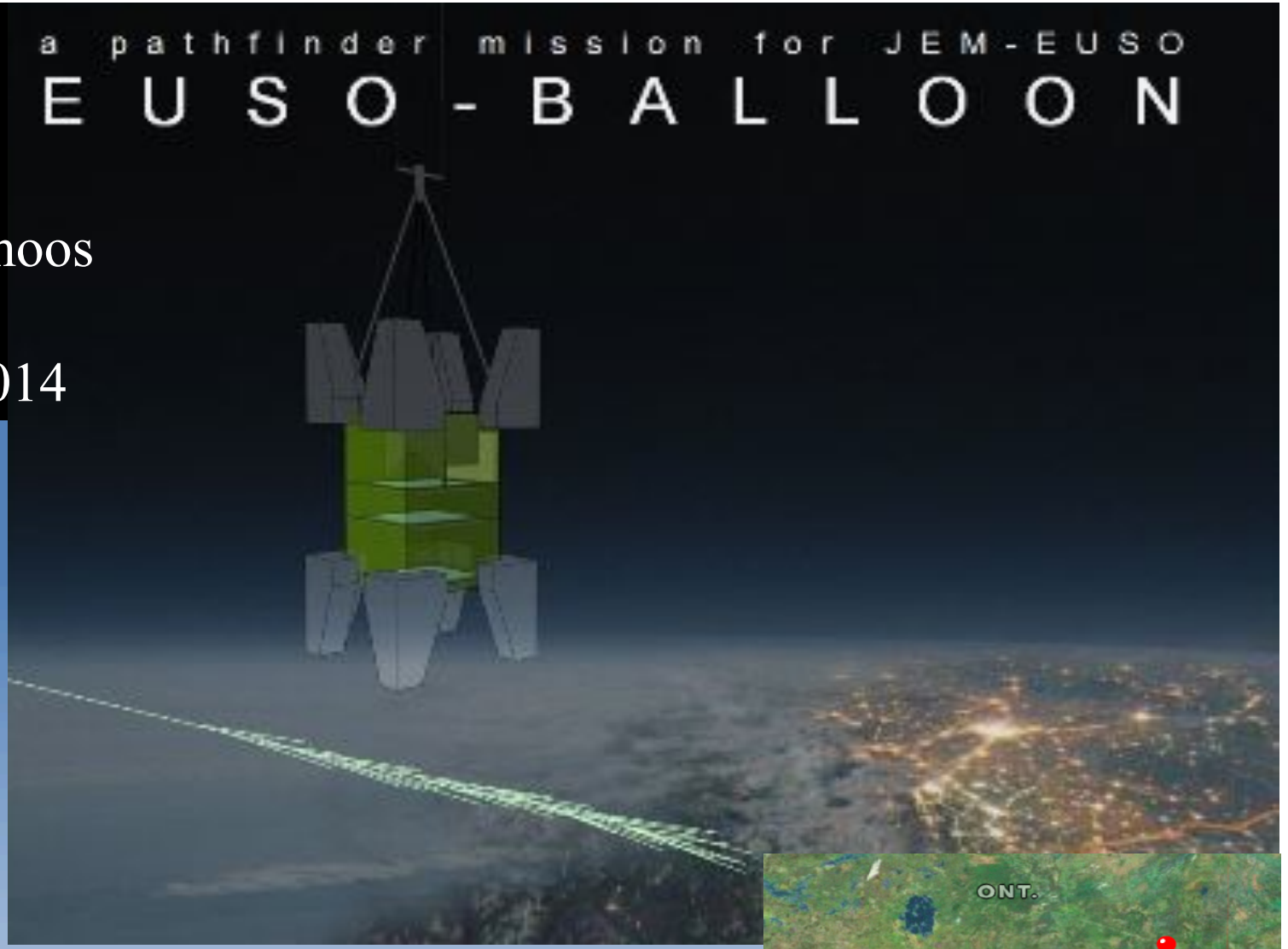
2. EUSO-BALLOON:
3 Balloon flights; 1st from
Timmins, Canada 2014
CNES
(French Space Agency)

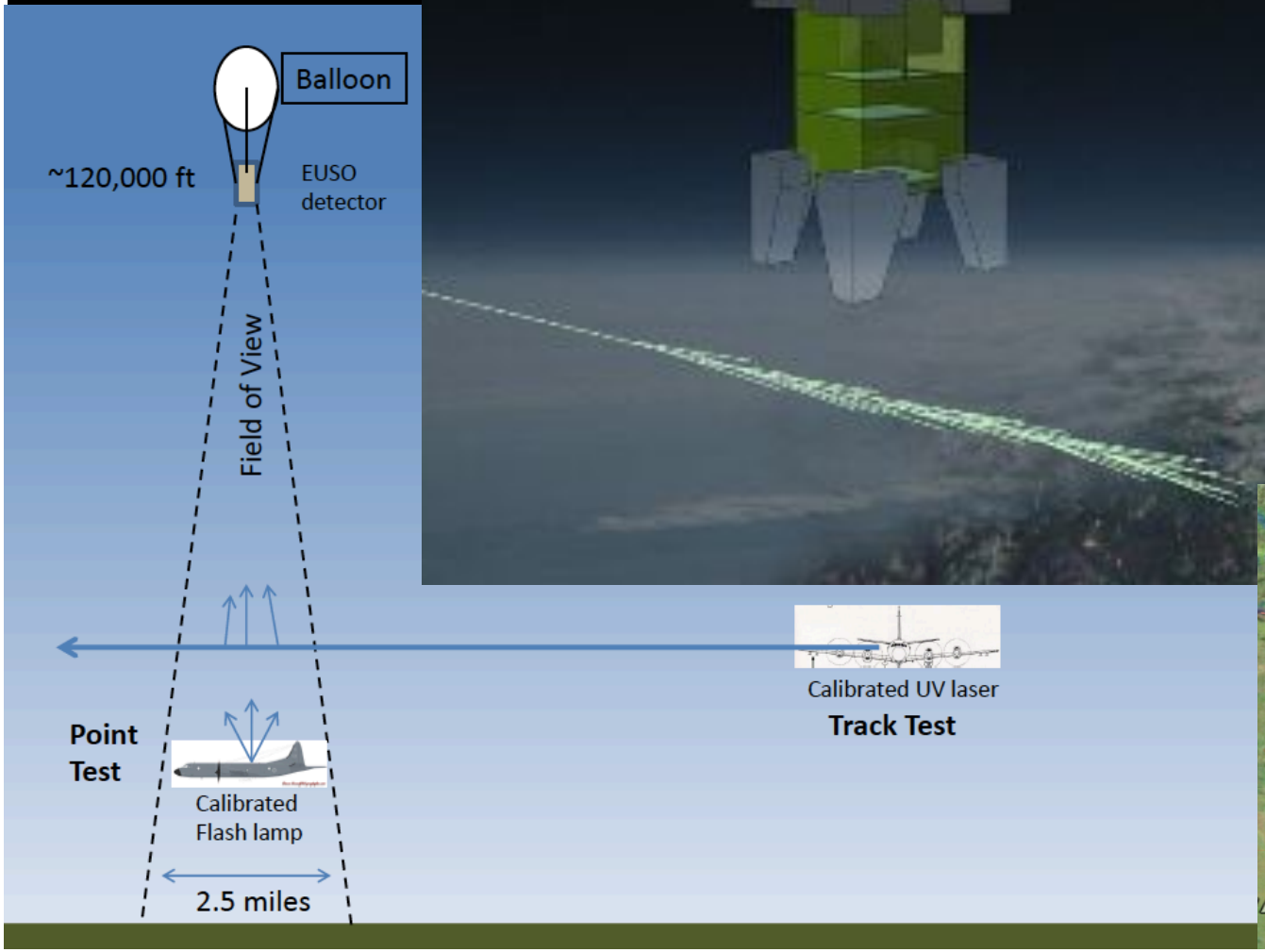


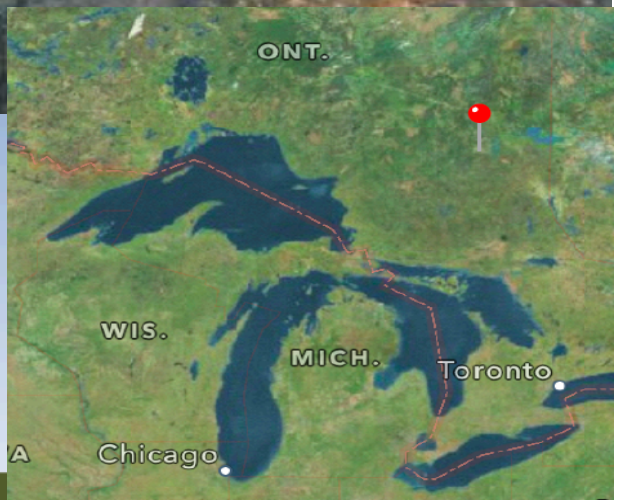
a pathfinder mission for JEM-EUSO

EUSO-BALLOON

PI: P. von Ballmoos
Phase C/D
Flight in Fall 2014







How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

JEM-EUSO

~200 events > 60 EeV/yr

Earth - surface ~ 5 10^8 km^2

~3.4 10^6 events/yr

How many UHECRs > 60 EeV?

Auger + TA ~30 events/yr

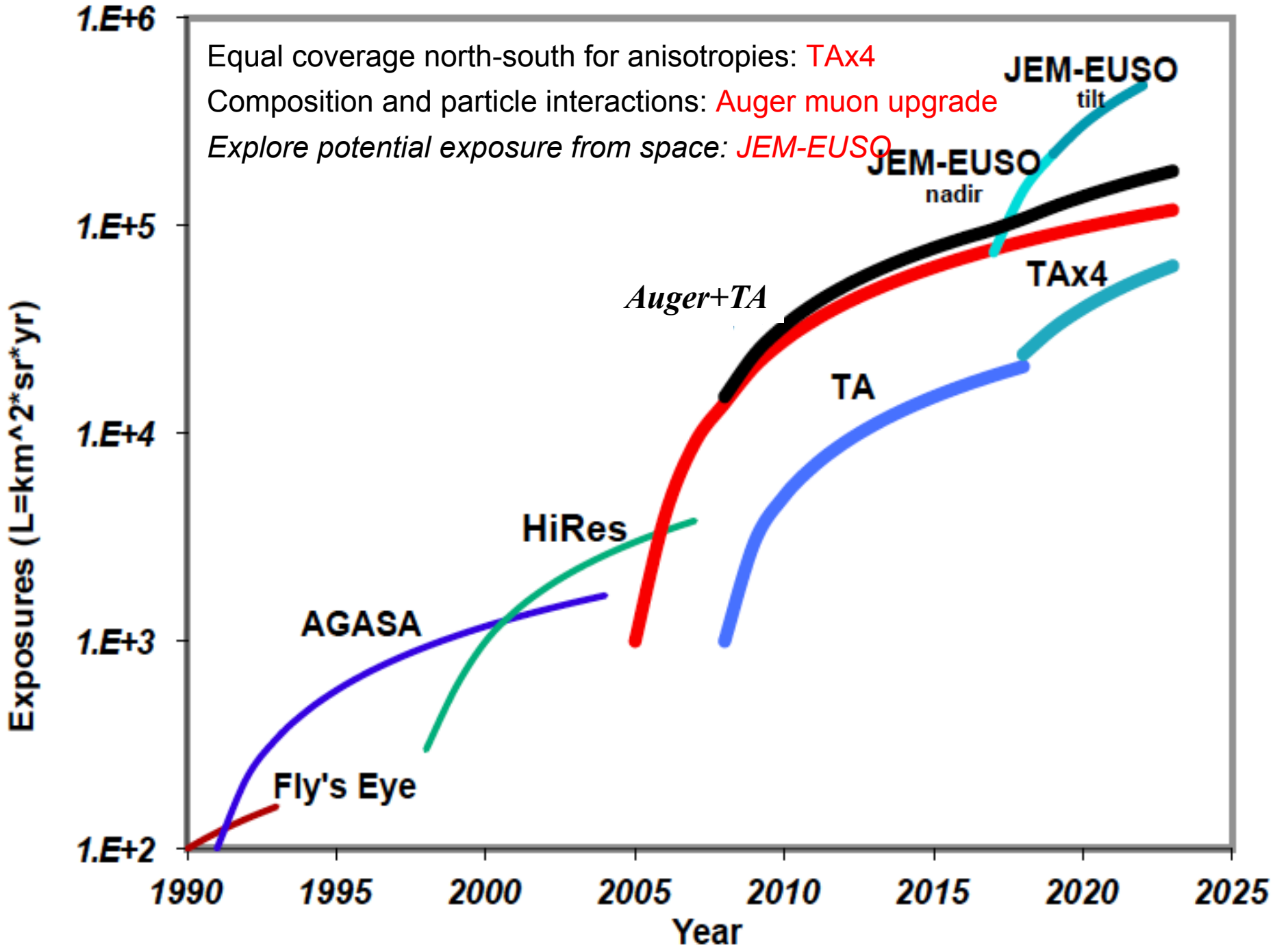
JEM-EUSO

~200 events > 60 EeV/yr

4 o.o.m to go!

Earth surface ~ 5 10^8 km^2

~3.4 10^6 events/yr


Equal coverage north-south for anisotropies: TAx4
Composition and particle interactions: Auger muon upgrade
Explore potential exposure from space: JEM-EUSO
JEM-EUSO
tilt
JEM-EUSO
nadir
TAx4
Auger+TA
TA
HiRes
AGASA
Fly's Eye
1.E+6
1.E+5
1.E+4
1.E+3
1.E+2
Exposures (L=km^2*sr*yr)
1990
1995
2000
2005
2010
2015
2020
2025
Year


Mysteries of the
Extreme Energy Frontier
To be resolved...
Thanks!